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CONTRACT NO. DA-04-200-507-ORD-333
UNDER ARMY PROJECT NOS. 593-32-003 AND 593-32-005
PHASE REPORT NO. 9

EFFECT OF CONTROLLED WELD DEFECTS ON THE BALLISTIC PERFORMANCE OF 5083 ALUMINUM ALLOY WELDMENTS

M. B. Kasen

DEPARTMENT OF METALLURGICAL RESEARCH

SPOKANE, WASHINGTON

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Phase Report No. 9

EFFECT OF CONTROLLED WELD DEFECTS ON THE BALLISTIC PERFORMANCE OF 5083 ALUMINUM ALLOY WELDMENTS

By

M. B. Kasen

SUMMARY

Specialized welding techniques were used to produce 27 weldments that contained controlled variations in the types and severities of weld defects. The weld defects intentionally introduced into the 1-1/4-inch thick double V-groove butt weldments were: (1) gas porosity, (2) lack of root fusion, (3) distributed fine dross particles, and (4) coarse dross films. For each type of weld defect, one group of triplicate weldments was produced with the specific defect present in moderate concentration and a second triplicate set with the same defect present in severe concentration. A corresponding set of triplicate weldments with no weld defects was also produced.

The Frankford Arsenal tested one weldment from each set in a ballistic shock test which they devised for this purpose. The intentional weld defects adversely affected the ballistic performance of the weldments, but not to an alarming degree. In no case was brittle catastrophic failure of the aluminum weldments observed. It was estimated that the deleterious effect of the weld defects increased in approximately the following order: (1) no weld defects, (2) moderate dross films, (3) moderate lack of root fusion, (4) moderate, scattered fine dross, (5) severe lack of root fusion, (6) severe porosity, (7) moderate porosity, (8) severe, scattered fine dross, and (9) severe dross films.

An ultrasonic weld inspection technique was found to be reasonably adequate for detecting the presence of weld defects, but probably inadequate for discriminating defect types and determining defect severity. Tests showed that radiography was primarily useful as a weld quality

inspection technique in determining weld porosity, but was completely insensitive in establishing the presence of dross defects. It appeared that lack of fusion and dross defects could be satisfactorily determined only by destructive inspection methods.

INTRODUCTION

In a preceding phase of this contract (Ref 1), a study was made of a series of sample weldments representing the most critical weld designs utilized in the aluminum-armored T113 personnel carrier. These sample weldments were obtained from the vehicle manufacturer. The quality of the weldments was reported to be "typical of the quality in the first three aluminum (T113) hulls fabricated." Our examination of these weldments revealed that many contained a great deal of coarse porosity.

It seemed probable that the presence of such severe weld defects might deleteriously affect the ballistic performance of the personnel carriers. Accordingly, it appeared desirable for Ordnance to establish minimum standards for the weld quality that would be acceptable in such vehicles. These standards could then be used by the vehicle manufacturer as a "go, no go" basis for accepting or repairing the individual welds produced in the course of vehicle fabrication.

Acceptance standards for weld quality are not new in principle. For example, the ASME Unfired Pressure Vessel Code (Section 8) and various military specifications for procurement of welded aluminum items specify minimum standards for acceptable weld quality in terms of reference radiographs which illustrate the maximum tolerable degrees of porosity, lack of fusion, cracking, etc. Unfortunately, these existing specifications are primarily concerned with obtaining satisfactory end performance of some type other than acceptable ballistic behavior, and no information existed to demonstrate that similar standards of weld quality would necessarily apply to the problem of assuring satisfactory ballistic performance from aluminum weldments. The present investigation was, therefore, undertaken to develop basic information about the effects of various types and severities of weld defects on the ballistic properties of aluminum armor plate weldments. This information was needed so that Ordnanc would have a sound basis for specifying realistic weld quality standards for use in military vehicle fabrication.

The types of weld defects studied in this investigation were those which might occur accidentally in production weldments for any of a number of causes. For example, porosity in a weldment can occur (1) as a result of a momentary loss of shielding, (2) from use of welding wire having a hydrated oxide or oily surface finish which causes hydrogen contamination of the weld pool, or (3) from utilizing too low welding current, too high voltage or too fast welding rate. Dross entrapment in a weldment can result from poor preliminary cleaning of the joint surfaces or insufficient brushing of preceding passes, or from loss of shielding, spatter ahead of the weld, etc. Lack of fusion can be due to improper welding procedures or inappropriate joint designs. Weld cracking can result from cooling stresses under conditions of high joint restraint. In fact, any of these defects might occur quite accidentally during the normal production of aluminum weldments despite ordinary precautions to prevent their happening.

For purposes of ballistic evaluation, it was considered desirable to utilize lengths of weldments which contained only a single type of weld defect, present in controlled concentration and uniformly distributed throughout the weld length. From previous welding investigations and experience, the Department of Metallurgical Research of Kaiser Aluminum & Chemical Corporation was able to propose several promising techniques for producing such special weldments. For example, it had previously been found that the amount of porosity in a weldment is a direct function of the amount of hydrogen available to the welding arc; hence, it appeared that precisely controlled additions of hydrogen to the shielding gas should produce correspondingly controlled amounts of weld metal porosity. In like manner, finely dispersed dross flakes could be produced in a weld in varying degree by varying oxygen additions to the welding arc. Coarse dross film could be intentionally introduced by welding over beads that had not been previously brushed, using a sufficiently low welding current so that the subsequent deposit of metal did not penetrate the oxide film on the preceding layer. Lack of root fusion could be produced intentionally by tightly butting the root faces and controlling the penetration of the root passes.

The investigation was carried out in three stages. First, nine groups of special weldments were produced using the techniques outlined above to obtain controlled weld defects of specific types and concentrations. This is described in Part I of the report. The defect concentrations in these weldments were then evaluated by both nondestructive and destructive examination techniques, as detailed in Part II. Finally, the weldments were tested in a ballistic shock test devised and performed by the Frankford Arsenal. The procedures and results of these tests are given in Part III.

PROCEDURES AND RESULTS

PART I

PRODUCTION OF WELDMENTS CONTAINING CONTROLLED DEFECTS

Nine sets of triplicate weldments each were produced for ballistic evaluation. One set was produced so as to contain a moderate concentration, and a second set so as to contain a severe concentration of one type each of four specific types of weld defects, namely: (1) gas porosity, (2) scattered fine dross, (3) coarse dross films, and (4) lack of root fusion. The ninth set was then produced without weld defects of any type to serve as a control or reference in evaluating the effects of the weld defects introduced into the other eight sets of weldments.

Materials

All 27 weldments were made from 1.25 inches thick 5083 alloy plate having mechanical properties and chemical composition as listed in Table I.

The filler wire was 3/32 inch diameter 5183 alloy with a zincate finish. Preliminary tests had demonstrated that this wire was capable of consistently producing welds showing no porosity that could be detected radiographically.

Equipment

Automatic MIG welding was used throughout. The automatic welding fixture is shown in Figure 1. It consisted of a rigidly mounted welding torch with Sigma drive unit, and a Linde Model CM 30 HW travel carriage to move the work piece under the stationary head. Welding current was obtained from a Westinghouse RA rectifier power supply.

Joint Design

For ease of subsequent ballistic evaluation, a flat, butt-weld joint design was chosen. Completed weldments were 1-1/4" x 12" x 15", with 15" weld length. A typical finished weldment is shown in Figure 2.

The butt joint had a 70° double V-groove joint design as shown in Figure 3. A 1/8" root face and 1/8" root opening were used in producing the reference welds (no defects) and the weldments that contained intentional porosity, scattered dross and coarse dross films. A copper backup bar was utilized, as illustrated in Figure 3. The pass sequence is shown in Figure 4. No passes were back-chipped.

A similar joint design with modified root face dimensions and root opening was used in producing the weldments with intentional lack-of-root-fusion defects. The moderate lack-of-fusion condition was obtained by using 1/8" root faces tightly butted together without a root opening. For the severe lack-of-fusion condition, tightly butted 1/4" root faces were employed. The joint designs and pass sequences are shown in Figure 5.

Welding Conditions

Details of the welding conditions used in producing all special weldments are summarized in Table II.

Obtaining Various Levels of Porosity

Welds with the desired degrees of porosity were produced by introducing hydrogen, as a mixture of 5% hydrogen + 95% argon, to the arc area through the contact tube of the welding torch. This technique for producing porosity was previously developed by our laboratory, and has already been described (Ref 2).

The following table summarizes the conditions used for obtaining porosity:

Number of Weldments Produced	Weldment Identifications	Degree of Porosity	Shielding Gas Used in MIG Welding: Regular Nozzle Type	Regular Nozzle Flow Rate	Contact Tube Type	Contact Tube Flow Rate
3 (controls)	L212, L243, L244	None	Argon	80 cfh	None	None
3	L240, L241, L242	Moderate	Argon	80 cfh	Argon + 5% H_2	4.5 cc/min
3	L235, L236, L237	Severe	Argon	80 cfh	Argon + 5% H_2	9.0 cc/min

Obtaining Various Levels of Scattered Dross

It was necessary to distinguish between scattered fine dross particles and coarse dross films. Scattered fine dross develops from the presence of oxygen in the arc area, such as might result from air entrainment into the shielding gas. It gives a peppered appearance to the surface of a weld fracture as illustrated in Figure 12. Dross films, on the other hand, result primarily from lack of fusion between passes in a multipass weld, particularly when preceding beads have not been wire brushed.

In this study, scattered dross was produced by introducing oxygen to the arc area through the contact tube of the welding torch, as follows:

Number of Weldments Produced	Weldment Identifications	Degree of Scattered Dross	Shielding Gas Used in MIG Welding			
			Regular Nozzle		Contact Tube	
			Type	Flow Rate	Type	Flow Rate
3 (controls)	L212, L243, L244	None	Argon	80 cfh	None	None
3	L229, L230, L231	Moderate	Argon	80 cfh	Oxygen	100 cc/min
3	L226, L227, L228	Severe	Argon	80 cfh	Oxygen	300 cc/min

Obtaining Various Levels of Dross Films

The welding condition conducive to the formation of dross films occurs when a large amount of weld metal rolls out over the top of unmelted underlying weld metal or parent metal. This is accomplished by increasing the arc length so that the heat of the arc becomes less concentrated on the work piece.

In this study, the weldments with dross film defects were produced by using a long arc length with low welding current as shown in the following table:

Number of Weldments Produced	Weldment Identification	Extent of Dross Films	MIG Welding Procedure		
			Voltage Across Arc	Arc Length	Amperes
3 (controls)	L212, L243, L244	None	24	5/16	360
3	L216, L217, L218	Moderate	25	3/8	310
3	L213, L214, L215	Severe	27	1/2	310

Obtaining Various Levels of Lack of Fusion

Lack of root penetration or fusion in an aluminum weldment can be caused by using too long an arc length, too low a welding current, or too thick root faces in the joint design. Of these potential causes, the most easily controlled for the purposes of the present study was joint design.

The weldments with intentional lack-of-fusion defects were accordingly produced by varying the root face size and root opening as shown in the following table:

Number of Weldments Produced	Weldment Identification	Degree of Lack of Root Fusion	Joint Design	
			Root Face	Root Opening
3 (controls)	L212, L243, L244	None	1/8"	1/8"
3	L223, L224, L225	Moderate	1/8"	None
3	L220, L221, L222	Severe	1/4"	None

PART II

DETECTION AND EVALUATION OF THE WELDMENT DEFECTS

It was expected that the different types and quantities of weld defects would produce differences in the ballistic behaviors of the nine groups of special weldments prepared in Part I. Therefore, it was important to determine to what extent these defects could be detected and evaluated by various nondestructive methods of weld inspection. Such data, when correlated with the corresponding ballistic behaviors, would then be useful as a basis for setting inspection standards for the weld quality desired in vehicle weldments.

Accordingly, the following tests were carried out. First, all 27 of the sample weldments were radiographed. Then, one weldment was selected at random from each of the nine sample groups and inspected carefully by an ultrasonic technique. Finally, destructive examinations were carried out in a few cases, with additional weldments identical to those produced for ballistic testing. The destructive tests included visual examinations of weld fracture specimens, and macroexamination and radiography of thin transverse weld sections.

Radiographic Inspection

Of the four types of weld defects studied, only porosity was clearly and satisfactorily revealed by radiography. Photographic reproductions of typical sections of the radiographs obtained for each of the three levels of porosity in the ballistic weld samples are shown in Figure 6. It may be noted that the quality of the control welds was indeed excellent. The amount of porosity present in the "moderate" porosity weldments is equal to, or slightly greater than that acceptable by the radiographic standards of ASME Unfired Pressure Vessel Code (Section 8). The weldment containing "severe" porosity would be unacceptable by any standard.

In the case of the weldments containing lack of root fusion, the ability to detect this condition radiographically was found to be quite erratic. This was not unexpected. The weldments had been produced by butting the root faces tightly together. Shrinkage of the deposited weld metal should then have forced these faces into even more intimate contact, preventing formation of a gap or void of sufficient size to be revealed by radiography. Furthermore, detection of even a small gap between root faces depends critically upon the x-ray beam being oriented directly along the plane of unfused area. If the radiation source is offset by only a small angle from this critical beam orientation, then the effective path length of the beam through the void is drastically reduced and detection sensitivity for the defect is correspondingly lost.

To demonstrate this limitation of radiography, a supplemental test was conducted. A weldment was produced in 1-1/4" 5083 plate under conditions which would provide a continuously decreasing amount of lack of fusion, and corresponding unfused gap width, from one end of the weld to the other. The joint design was similar to that illustrated in Figure 3. The variation in lack of fusion was obtained by varying the width of the root opening from 0 to 1/8" in the 15" length of weld. After radiographic examination, the weld was sectioned at four places along the length to obtain 1/4" thick slices transverse to the weld. The slices themselves were radiographed, and then etched for macroexamination. The results of this study are shown in Figure 7. Very close examination is required in order to detect the lack of fusion in the radiograph of the full weld thickness. However, the defect indication may be seen as a straight line somewhat darker than surrounding portions of the radiograph. The actual amount of lack of fusion is shown by the macrosections and the radiographs of the transverse slices.

It is of interest to note that some fine porosity is clearly evident in the radiographs of the 1/4" thick transverse sections; however, this porosity is completely invisible in the normal radiograph through the full weld thickness. This fine porosity occurred at the interfaces between several of the passes. It represents an excellent example of an existing weld defect whose size is less than 1-2% of the total weld thickness and therefore below the detection sensitivity of the normal radiographic technique.

The radiographs of the weldments containing dross films and fine scattered dross revealed that neither of these defects could be satisfactorily detected by radiography. This is because the dross (aluminum oxide) has essentially the same radiographic absorption as the aluminum alloy itself, and is therefore undetectible.

To confirm this limitation of radiographic examinations, a supplemental study was conducted. Weldments containing dross films in four degrees of severity were produced. These different dross levels were obtained by using arc voltages of 24, 25, 26 and 27 volts, respectively. Each weldment was radiographed after completion. Then, the welds were examined further by making fracture tests both longitudinal and transverse to the welding direction. The results of the study are shown in Figure 8. Both the longitudinal and transverse weld fractures clearly show the presence of severe amounts of dross films in the welds made with longer arcs and higher voltages, whereas the radiographs fail completely to reveal these defects.

Ultrasonic Inspection

The availability of the series of weldments containing known defects in two ranges of severity provided us with a unique opportunity to determine whether ultrasonic inspection techniques could discriminate between such defects. This was important because ultrasonic inspection techniques have received rather wide acceptance as a means of preliminary inspection of weld quality. In such usage, the ultrasonic examination is frequently utilized merely to indicate whether a defect may exist in a weld. When a defect is indicated, further inspection by more conventional procedures is then undertaken.

For this study, one weldment was selected at random from each of the nine ballistic sample groups. A water immersion testing procedure was utilized, with the ultrasonic testing direction oriented as illustrated in Figure 9. A Sperry UR Reflectoscope with a 5 megacycle, 3/4" diameter immersion type quartz transducer was used. A Hitt Standard Test Block with 3/64" diameter flat-bottomed hole located 5-3/4" from the test surface was used as reference. Instrument settings were adjusted to provide a 3" peak-to-peak defect indication for this reference condition. Figure 10 is a sketch which identifies the components of the typical trace pattern on the Reflectoscope cathode ray tube.

The results of the ultrasonic inspections are summarized in the illustrations shown in Figures 6, 11, 12 and 13. For each type of weld defect and severity, the typical Reflectoscope trace is compared with the corresponding defect indication obtained by the most suitable conventional inspection technique for that type defect (ie, radiography, weld fracture, or macrosection).

An excellent correlation was obtained between the severity of weld porosity and the size of the ultrasonic indication of this porosity (Figure 6).

A correlation was also found between the severity of the dross film defect and the ultrasonic indication of this defect (Figure 11).

The ultrasonic traces obtained from welds containing scattered fine dross gave indications of the presence of this defect, but did not provide sufficient differences in indications to discriminate between the different defect severities (Figure 12).

For the weldments containing lack of root fusion (Figure 13), a weaker ultrasonic defect indication was obtained from the weld which contained "severe" lack of root fusion than from the weld which contained this defect in "moderate" degree. The defect indication from the "severe" lack of root fusion appeared to be anomalously low. A possible explanation for this anomaly may be that shrinkage contraction of the filler metal in this particular weldment forced the unpenetrated root faces into sufficiently excellent mechanical contact that the ultrasonic beam could, to some extent, be propagated across the unfused mating root faces and thus exhibit less reflection from this defect than if an actual air gap had existed between the unpenetrated root surfaces.

PART III

BALLISTIC TESTS OF THE WELDMENTS

The ballistic tests were performed by the Frankford Arsenal. All 27 weldments produced in Part I were forwarded to the Arsenal for this purpose. Several additional weldment samples with uncontrolled defects were also supplied for use in establishing the ballistic test procedure.

Ballistic Test Procedure

The Frankford Arsenal furnished (Ref 3) the following description concerning the ballistic test procedure employed:

"Test Procedure for Ballistic Shock Test of Experiment Weldments

Nature of Test:	Test designed to evaluate ballistic shock resistance of weldments. In the absence of an explosive impact, a soft projectile which would deform or mushroom on impact was therefore used to simulate an explosive type test.
Projectiles:	2024-0 aluminum; 30 mm caliber; projectiles made to lengths of 1-3/16 in. and 3-1/4 in.; the 3-1/4 in. projectile was fired first, followed by the 1-3/16 in. projectile against each plate; hardness of most projectiles was 22 to 24 R_b; a few of the projectiles possessed hardness of 18 to 19 R_b and 25 to 26 R_b.
Velocity:	All projectiles impacted at approximately 2300 f/s.
Note:	No consistent difference found in appearance of weldments impacted with projectiles of 3-1/2 in. vs 1-3/16 in. lengths; all plates showed fairly large bulges at rear."

Only one sample from each of the nine sets of weldments was tested.

Photographs showing the appearance of the back surface of these weldments after ballistic shock testing are reproduced in Figures 14 to 22. These photographs were taken and supplied by the Frankford Arsenal. The back surface is defined as the side opposite the surface impacted by the projectiles.

Ballistic Test Results

The Frankford Arsenal furnished (Ref 3) the following description of their evaluation of the results of the ballistic tests:

> "No quantitative evaluation of the shock tested weldments was made beyond a visual examination of the plates. On this basis it was found that all of the samples containing controlled defects appeared somewhat inferior to the controlled weld sample (plate L212) with respect to the degree of penetration and/or extent of cracks developed. Of the controlled defect series, weldments containing moderate dross film and moderate lack of fusion appeared to be possibly least affected by the shock test. In the case of the porosity samples, the one containing moderate porosity appeared to have a slightly greater degree of cracking than did the one with severe porosity. In the remaining three series, ie, dross film, finely distributed dross, the lack of fusion, the sample containing the severe degree of the respective defect appeared somewhat more affected by the shock test, this difference being most pronounced in the case of the sample with finely distributed dross. Further comparison of the ballistic results by your company may be possible with the aid of the enclosed photographs.
>
> "The above represent only one set of the triplicate series of plate weldments from your company which has thus far been tested. Owing to the rather minor nature of the differences shown by some of the fired samples, it would appear advisable to continue with tests of the remaining samples in order to obtain more conclusive data."

To supplement the Arsenal's evaluation, the photographs showing the ballistic shock damage sustained by the weldments were carefully examined by this laboratory. The results of this examination are summarized in Table III. From this tabulation, the weldments were ranked in estimated order of increasingly severe damage sustained, as follows:

1. No weld defects (control weldment)
2. Dross films, moderate
3. Lack of root fusion, moderate
4. Scattered fine dross, moderate
5. Lack of root fusion, severe
6. Porosity, severe
7. Porosity, moderate
8. Scattered fine dross, severe
9. Dross films, severe

It may be noted that the above order of increasing detrimental effect of weld defects is in complete agreement with the Frankford Arsenal's less detailed ranking of these effects.

DISCUSSION OF RESULTS

It is probably significant that all weldments containing defects showed more extensive cracking than the high-quality control weldment (no weld defects) in the ballistic shock test. This indicates that weld defects have at least some adverse effect upon the ballistic performance of weldments. However, it is important to note that even the worst weld defects did not lead to brittle catastrophic failure of the aluminum weldments. Moreover, the most severe damage encountered was still of a highly localized character, and not of alarming magnitude.

The weld cracking that occurred upon ballistic impact was longitudinal in the majority of cases. These longitudinal cracks developed principally at the junctions between two beads, or at the fusion line. It is not known at this time whether these crack locations were due to the mechanical notches formed by the natural geometries of the weld beads, or to the metallurgical notches created by differences in metallurgical structures at these locations, or possibly to both causes. Accordingly, it would appear desirable to ballistically test one of the duplicate sets of weldments after machining the weld beads flush and smooth to eliminate the mechanical notches from the weld bead geometries. If the observed mode of cracking remained the same with beads machined flush, it perhaps could be concluded that the metallurgical notch between beads or at the fusion line would always make the weldments susceptible to longitudinal fracture upon ballistic impact. On the other hand, if an improvement in performance were noted, it would suggest that removal of mechanical notches might improve the ballistic performance of aluminum weldments.

Weldments which contained scattered random defects throughout the weld metal exhibited scattered random cracking in the transverse direction as well as longitudinal cracking. Longitudinal defects of relatively small cross-sectional area, such as minor lines of no-fusion or moderate dross films had only a very minor effect on ballistic performance. However, where the longitudinal defect consisted of a large area, as in the weldment containing large dross films, the strength of the remaining sound metal was insufficient to prevent severe cracking upon ballistic shock.

Of the weld defects having the most adverse effect on ballistic performance, only porosity could be adequately detected by radiographic inspection techniques. Fortunately, the other types of most severely detrimental weld defects (severe, scattered fine dross and severe, coarse dross films) can be avoided by proper welding techniques. For example, severe, scattered fine dross formation can be avoided by adequate shielding against drafts and by employing suitably high rates of gas flow in MIG welding. Severe dross films can be avoided by utilizing welding currents somewhat on the high side.

It appeared that ultrasonic inspection methods might be capable of nondestructively detecting the presence of dross films. However, the ultrasonic technique employed in this study would not be practical for field or shop use, since a completed weld would rarely be accessible for testing by the direct beam as indicated in Figure 9, nor is it practical to immersion test most weldments. The most practical ultrasonic technique for field and shop inspection of completed weldments would be by the contact method of testing with a shear wave crystal. Shear wave testing techniques would be expected to yield results roughly equivalent to those obtained with the direct beam technique utilized in the present study.

Unfortunately, the amount of ballistic testing performed in connection with this study does not appear to be sufficient to permit establishing definite minimum quality levels and inspection standards for aluminum weldments for ballistic service applications.

CONCLUSIONS

The following conclusions appear to be warranted from this investigation:

1. It is possible to produce welds containing precisely controlled amounts of porosity, scattered fine dross, coarse dross films, and lack of root fusion.

2. Weld defects of the above types have some adverse effect upon the ballistic performance of weldments. However, this adverse effect was not of alarming magnitude even in the case of the most severe defects studied.

3. Ballistic shock does not produce brittle catastrophic failure of 5083 alloy weldments, even when these weldments contain severe weld defects.

4. The adverse effect of weld defects on the ballistic behavior of 5083 alloy weldments increased in approximately the following order:

   (a) No weld defects
   (b) Moderate dross films
   (c) Moderate lack of root fusion
   (d) Moderate scattered fine dross
   (e) Severe lack of root fusion
   (f) Severe porosity
   (g) Moderate porosity
   (h) Severe scattered fine dross
   (i) Severe dross films

5. Radiography is a satisfactory inspection technique for detecting ballistically objectionable amounts of porosity defects in aluminum weldments.

6. The presence of dross defects, of either the coarse film type or the scattered, fine dross type, is best revealed by weld fracture examinations. These defects are not satisfactorily detected by radiography.

7. Lack of fusion (lack of root penetration) defects are frequently difficult to detect by radiography. They are best detected by macroexamination of weld cross-sections.

8. Porosity, dross, and lack of fusion defects are all revealed by ultrasonic inspection methods; however, the specific type of defect and, in some cases, the defect severity are difficult to determine. Hence, it appears that ultrasonic inspection techniques would be primarily useful for preliminary, rapid examination for the purpose of merely detecting the presence of weld defects, whereupon more costly inspection techniques, such as radiography or destructive section, could then be applied to limited weldment areas, only where needed.

9. It is important to use adequate shielding against drafts and to utilize sufficient shielding gas flow rates in MIG welding in order to prevent scattered dross formation in the weldments.

10. Welding currents should be on the high side to prevent extensive formation of coarse dross films and to obtain root fusion.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the help of L. E. Levchenko in preparing the special weld specimens used in this study. The contribution of A. T. Taylor in conducting the ultrasonic studies is also appreciated.

REFERENCES

1. J. B. Hess, "Contract No. DA-04-200-507-ORD-333, Phase Report No. 8, Development of Recommended Techniques for Radiographically Inspecting Seven Welded Joints of the T113 Vehicle," Kaiser Aluminum & Chemical Corporation,

2. M. B. Kasen and A. R. Pfluger, "Chlorine Additions for High-Quality, Inert-Gas Metal-Arc Welding of Aluminum Alloys," THE WELDING JOURNAL, Vol. 37, (1958), p. 269-s.

3. H. P. George to F. W. DeMoney, Letter, (Reference: ORDBA-1322; Mr. Porembski/mco/5221), December 31, 1958.

TABLE I

CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES OF THE 1-1/4 INCH THICK 5083 ALLOY PLATE USED IN THIS STUDY

Chemical Analysis, Per Cent by Weight

% Silicon	% Iron	% Copper	% Manganese	% Magnesium	% Chromium	% Zinc	% Titanium
0.13	0.24	0.03	0.70	4.47	0.12	0.06	0.01

Mechanical Properties

Ultimate Tensile Strength (psi)		Yield Strength (psi @ 0.2% offset)		Elongation (% in 2 inches)	
Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
45,750	44,850	34,650	30,000	16.5	19.0

TABLE II

WELDING CONDITIONS USED TO PRODUCE WELDS IN THE CONTROLLED DEFECT SERIES
(All Welds Produced in 1-1/4 Inch Thick 5083 Plate)
(All Welds Made With 3/32 Inch 5183 Wire)

Type of Defect	Degree of Defect	Main Gas Shield	Contaminant Gas	Pass Number	Welding Current	Arc Voltage	Travel Speed (ipm)	Joint Design Ref.	Weld Numbers
None	None	80 cfh Argon	None	1 & 3	360	24	18	Fig. 2	L212, L243, L244
				2 & 4	360	24.5	16		
				5 & 6	350	24.5	18		
				7 & 8	350	24.5	18		
				9, 10, 12 & 13	340	25	18		
				11 & 14	340	25	16		
Porosity	Moderate	80 cfh Argon	4.5 ccm H_2	1 & 3	360	24	18	Fig. 2	L240, L241, L242
				2 & 4	360	24.5	16		
				5 & 6	350	24.5	18		
				7 & 8	350	24.5	18		
				9, 10, 12 & 13	340	25	18		
				11 & 14	340	25	18		
Porosity	Severe	80 cfh Argon	8.9 ccm H_2	1 & 3	350	24	18	Fig. 2	L235, L236, L237
				2 & 4	350	24.5	16		
				5 & 6	340	25	18		
				7 & 8	340	25	18		
				9, 10, 12 & 13	330	25	18		
				11 & 14	330	25	18		
Dross (Scattered)	Moderate	80 cfh Argon	None	1 & 3	350	24	18	Fig. 2	L229, L230, L231
			100 ccm O_2	2 & 4	340	24.5	14		
			"	5 & 6	340	24.5	16		
			"	7 & 8	340	24.5	18		
			"	9, 10, 12 & 13	340	25	18		
			"	11 & 14	340	25	16		

TABLE II (CONT'D)

Dross (Scattered)	Severe	80 cfh Argon	None	1 & 3	350	24	18	Fig. 2	L226, L227, L228
			300 ccm O_2	2 & 4	330	24.5	14		
			"	5 & 6	330	25	16		
			"	7 & 8	330	25	18		
			"	9, 10, 12 & 13	330	25	18		
			"	11 & 14	330	25	16		
Dross Films	Moderate	70 cfh Argon	None	1 & 3	310	25	18	Fig. 2	L216, L217, L218
				2 & 4	310	25	15		
				5 & 6	310	25	18		
				7 & 8	310	25	18		
				9, 10, 12 & 13	310	25	18		
				11 & 14	310	25	18		
Dross Films	Severe	70 cfh Argon	None	1 & 3	310	27	18	Fig. 2	L213, L214, L215
				2 & 4	310	27	15		
				5 & 6	310	27	18		
				7 & 8	310	27	18		
				9, 10, 12 & 13	310	27	18		
				11 & 14	310	27	18		
Lack of Root Fusion	Moderate	80 cfh Argon	None	1 & 3	310	23.5	20	Fig. 4(a)	L223, L224, L225
				2 & 4	360	24	18		
				5 & 6	360	24	20		
				7 & 8	360	24	20		
				9, 10, 12 & 13	350	24.5	18		
				11 & 14	350	24.5	18		
Lack of Root Fusion	Severe	80 cfh Argon	None	1 & 3	310	23.5	20	Fig. 4(b)	L220, L221, L222
				2 & 4	360	24	18		
				5 & 6	350	24	18		
				7 & 8	350	24	18		
				9, 10, 12 & 13	350	24.5	18		
				11 & 14	350	24.5	18		

Note: Interpass temperature 150° or below. All plates cleaned with caustic and then desmutted in nitric acid before welding.

TABLE III

RESULTS OF VISUAL EXAMINATION OF PHOTOGRAPHS SHOWING WELDMENT DAMAGE PRODUCED IN BALLISTIC SHOCK TEST

	Weldment No.			
	L212	L240	L235	L229
Weld Defect	None	Porosity, Moderate	Porosity, Severe	Scattered Dross Moderate
Type of Cracks:				
Longitudinal	X	X	X	X
Transverse		X	X	X
Random		X		X
Straight	X	X	X	
Branching		X	X	X
Location of Cracks:				
Fusion Line	X	X		X
Between Beads	X	X	X	X
Random		X	X	
Plate				
Severity of Cracking:				
No. of large cracks	2	3	2	4
No. of small cracks	4	40	8	20
Dimension of largest cracks,				
Width	3/16	3/16	3/16	1/32
Length	1-3/4	1-3/4	2	1-1/2
Location of largest cracks	Fusion line; between beads	Between beads	Longitudinal with large transverse branches	Transverse
Estimated Order of Increasing Ballistic Damage	1	7	6	4

L226	L216	L213	L223	L220
Scattered Dross, Severe	Dross Films, Moderate	Dross Films, Severe	Lack of Root Fusion, Moderate	Lack of Root Fusion, Severe
X	X	X	X	X
X	X	X	X	X
X		X		
	X	X	X	X
X	X	X	X	X
	X		X	X
X	X	X	X	X
X	X	X		
		X		
2	2	2	2	2
40	10	10	2	5
9/16	3/16	1/2	1/4	5/16
2-1/4	2-1/4	2-1/4	2-1/4	1-3/4
Longitudinal with large transverse branches	Fusion line	Transverse across fusion line; between beads	Between beads	Between beads
8	2	9	3	5

A - Wire Spool
B - Wire Feed Motor
C - Pipe for Introducing Gas Down Contact Tube.
D - MIG Welding Barrel
E - Travel Carriage
F - Control Box

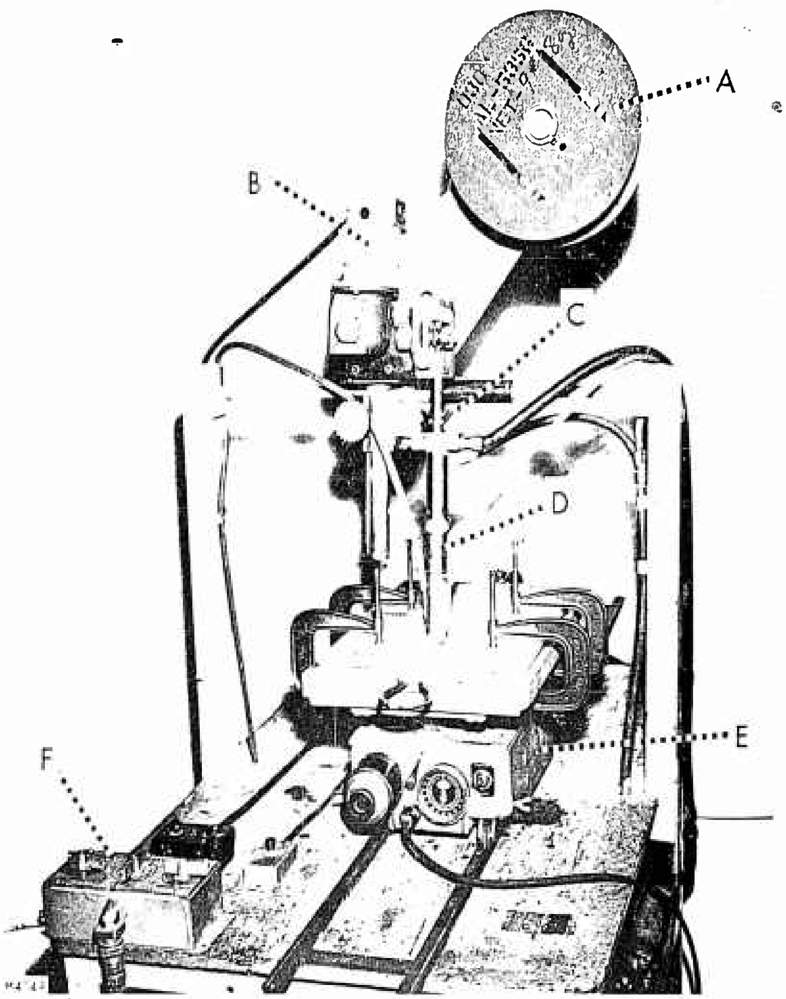


Figure 1
WELDING SET-UP USED FOR PRODUCING WELDS CONTAINING VARIOUS LEVELS OF SPECIFIC DEFECTS

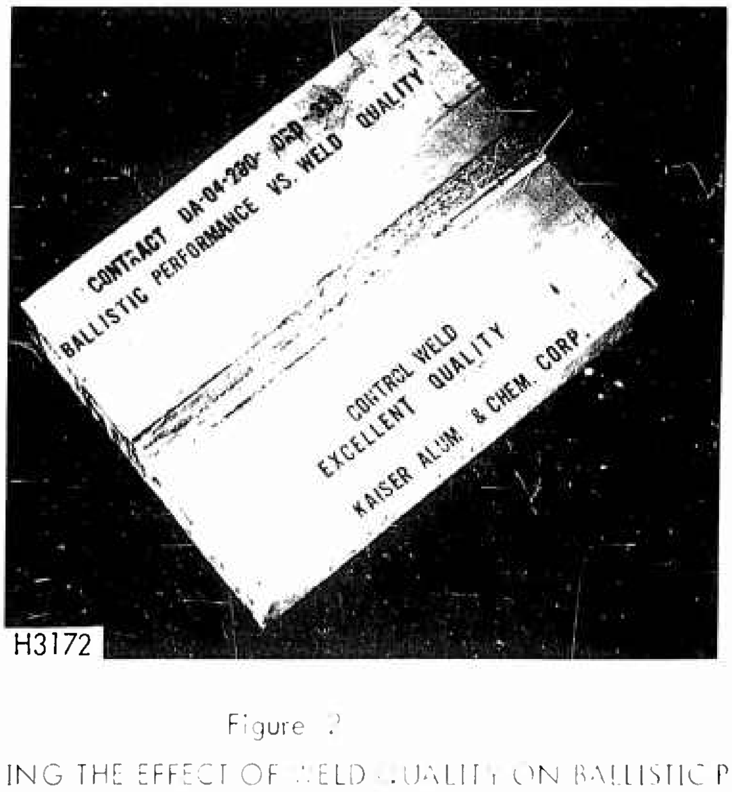
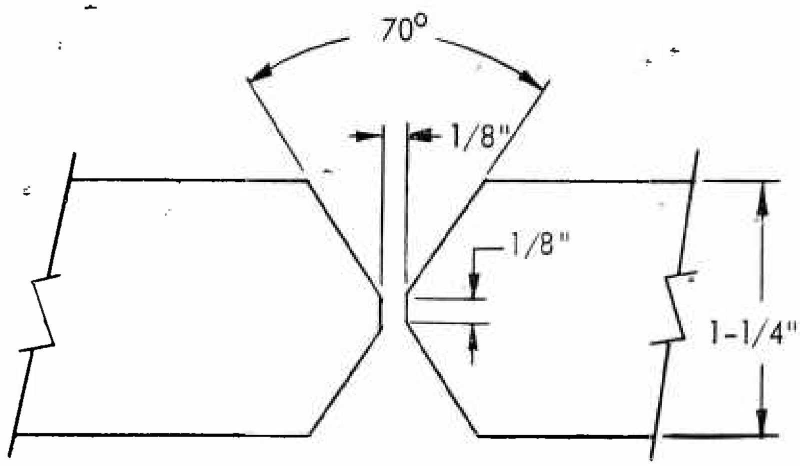
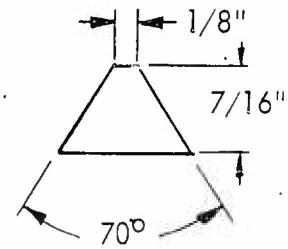


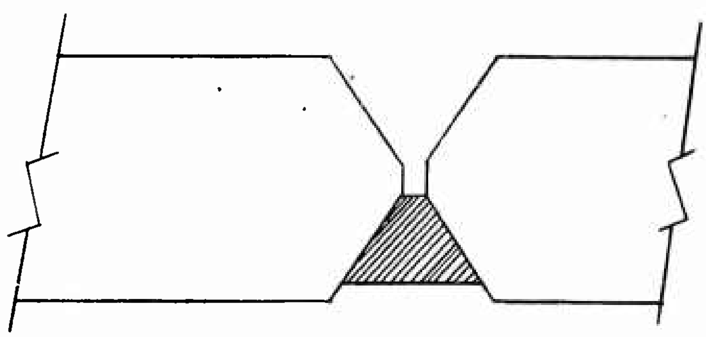
Figure 2
WELDMENT FOR DETERMINING THE EFFECT OF WELD QUALITY ON BALLISTIC PERFORMANCE



(a) Joint Design



(b) Backup Bar
(copper)



(c) Sketch of Joint Ready for First Pass

Figure 3

JOINT DESIGN AND BACKUP BAR CONFIGURATION USED TO PRODUCE WELDS WITHOUT DEFECTS (CONTROLS) AND WELDS CONTAINING CONTROLLED QUANTITIES OF POROSITY, SCATTERED DROSS AND DROSS FILMS

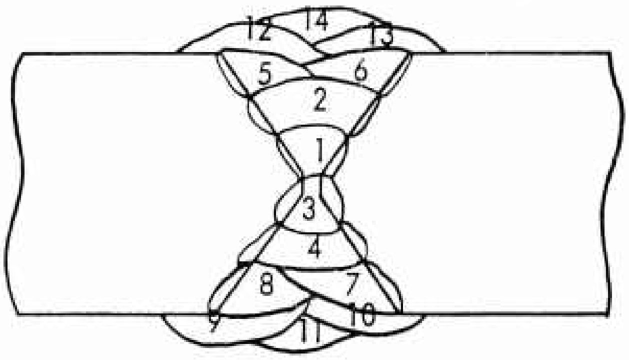
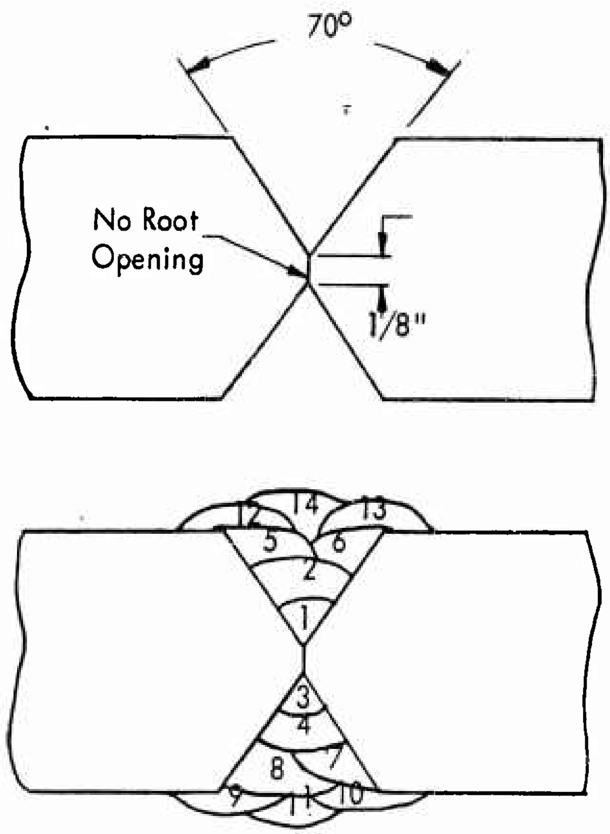


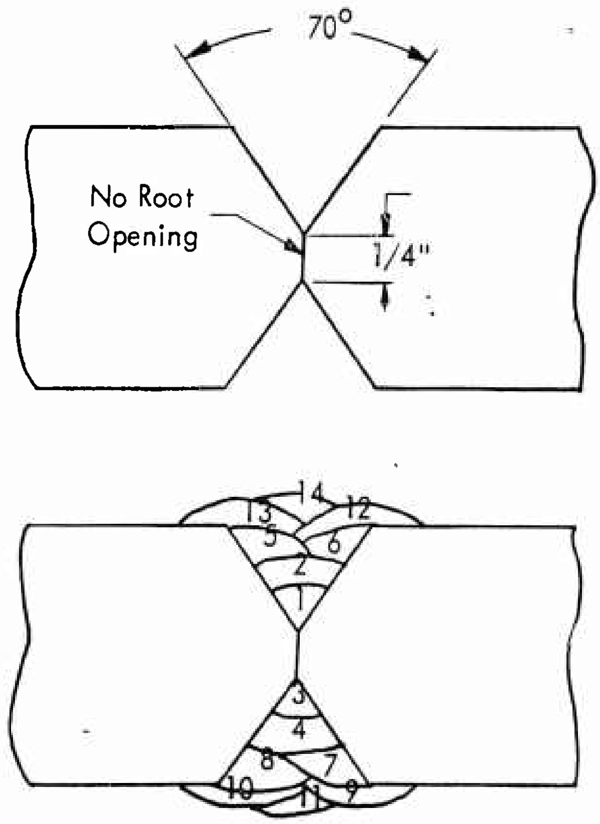
Figure 4

PASS SEQUENCE USED FOR WELDS CONTAINING NO DEFECTS (CONTROLS) AND FOR WELDS CONTAINING POROSITY, SCATTERED DROSS AND DROSS FILMS



(a)

Moderate Lack of Root Fusion



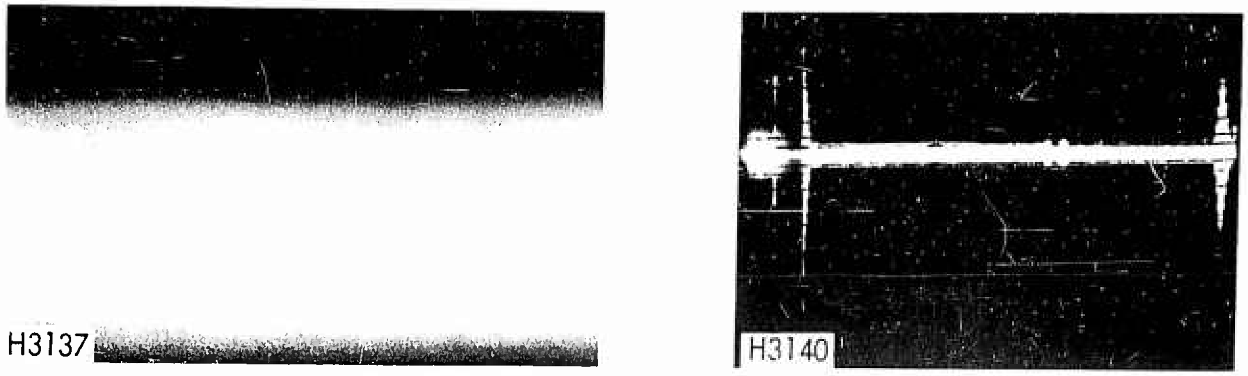
(b)

Severe Lack of Root Fusion

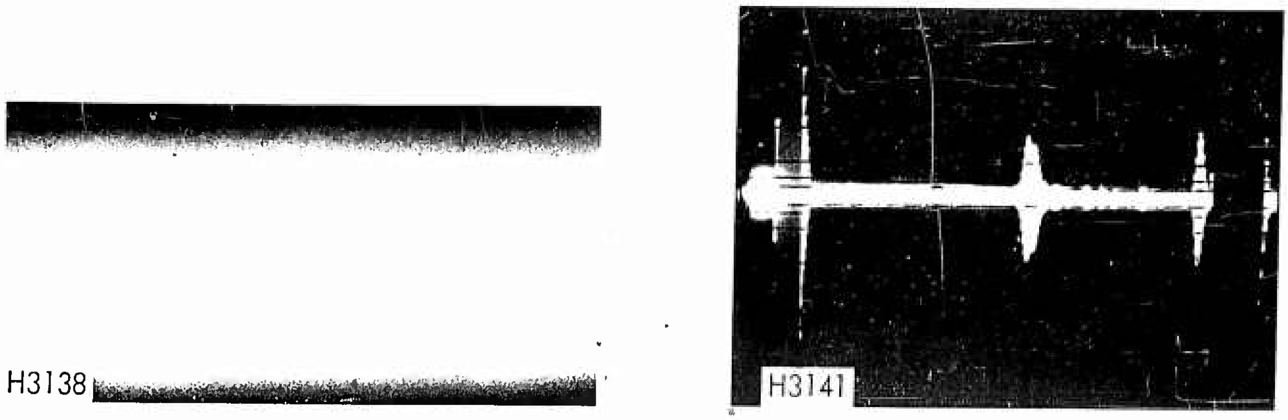
Figure 5

JOINT DESIGN AND PASS SEQUENCE USED TO PRODUCE VARYING DEGREES OF LACK OF ROOT FUSION

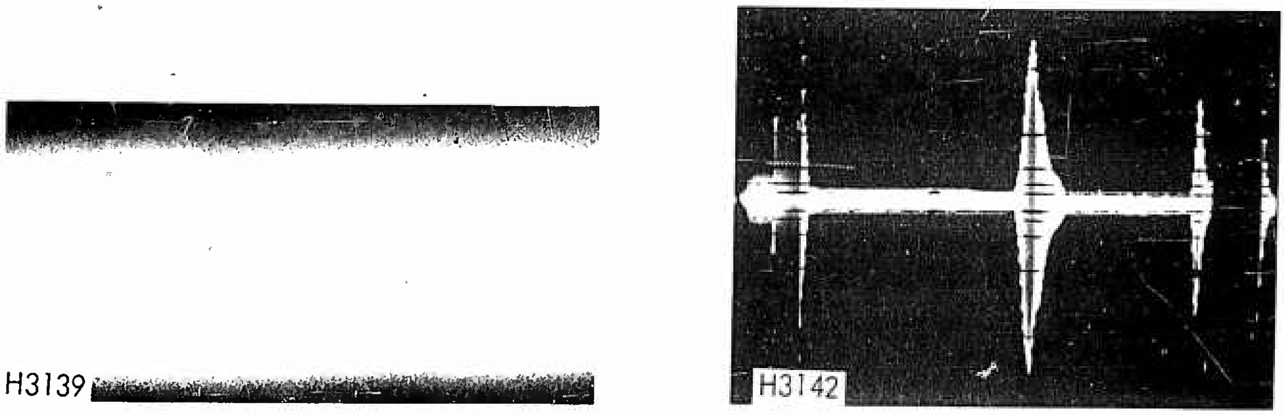
Photo Reporductions of Typical Radiographs | Typical Ultrasonic Response Patterns



(a) Control Weld (No Defects)



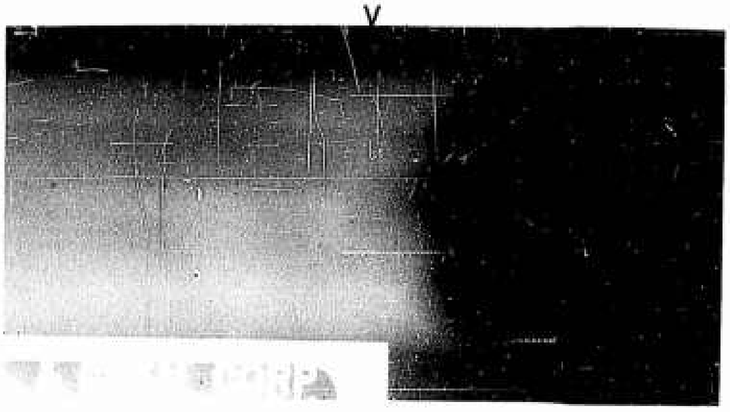
(b) Moderate Porosity



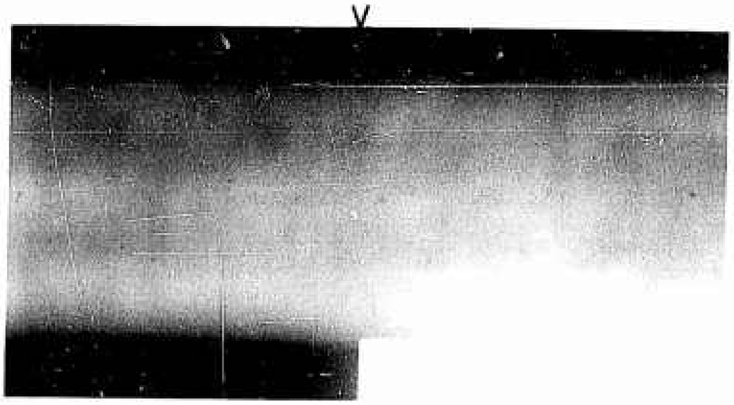
(c) Severe Porosity

Figure 6
POROSITY SERIES
Extent of Weld Defects as Determined by Radiographic and Ultrasonic Examinations

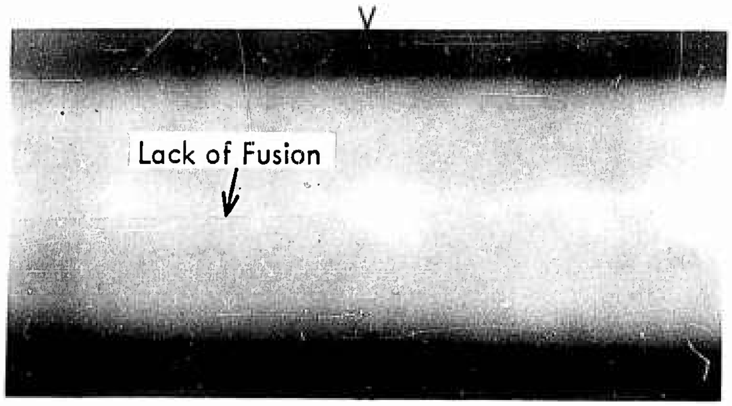
No Lack of Fusion



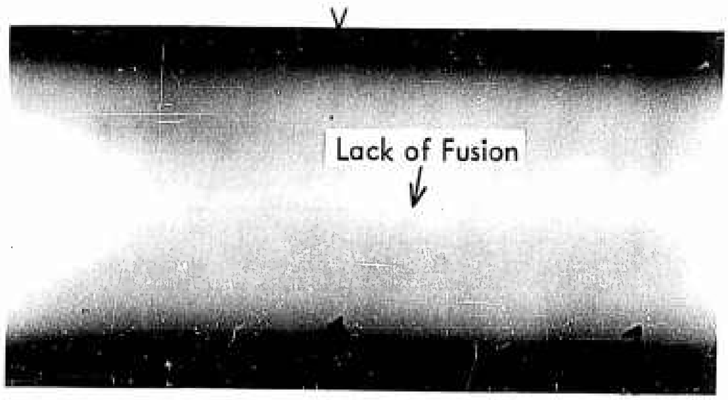
Slight Lack of Fusion



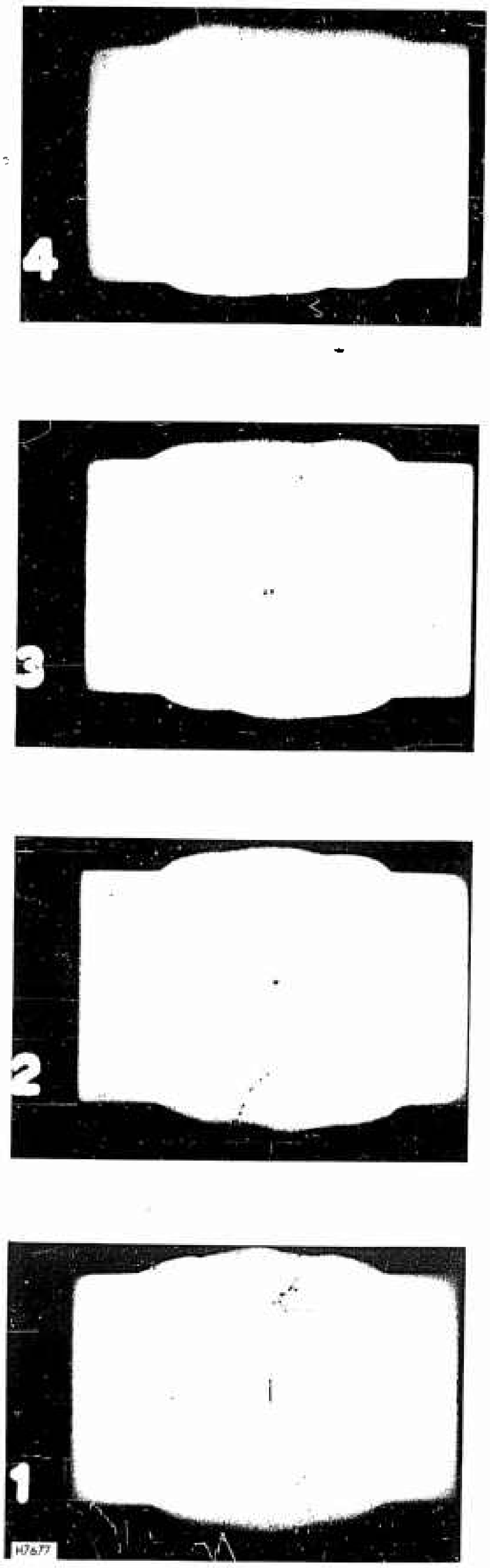
Moderate Lack of Fusion



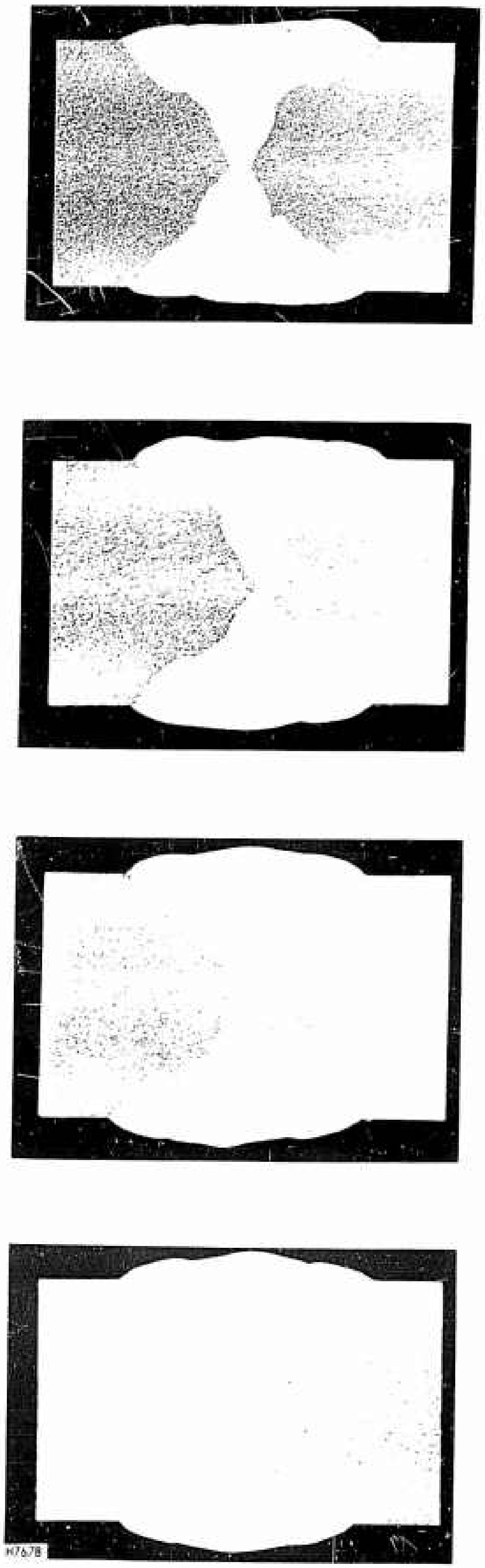
Severe Lack of Fusion



(a)
Conventional Radiograph
V Indicated Weld Location From which the Transverse Slices and Macro-Sections were Taken.



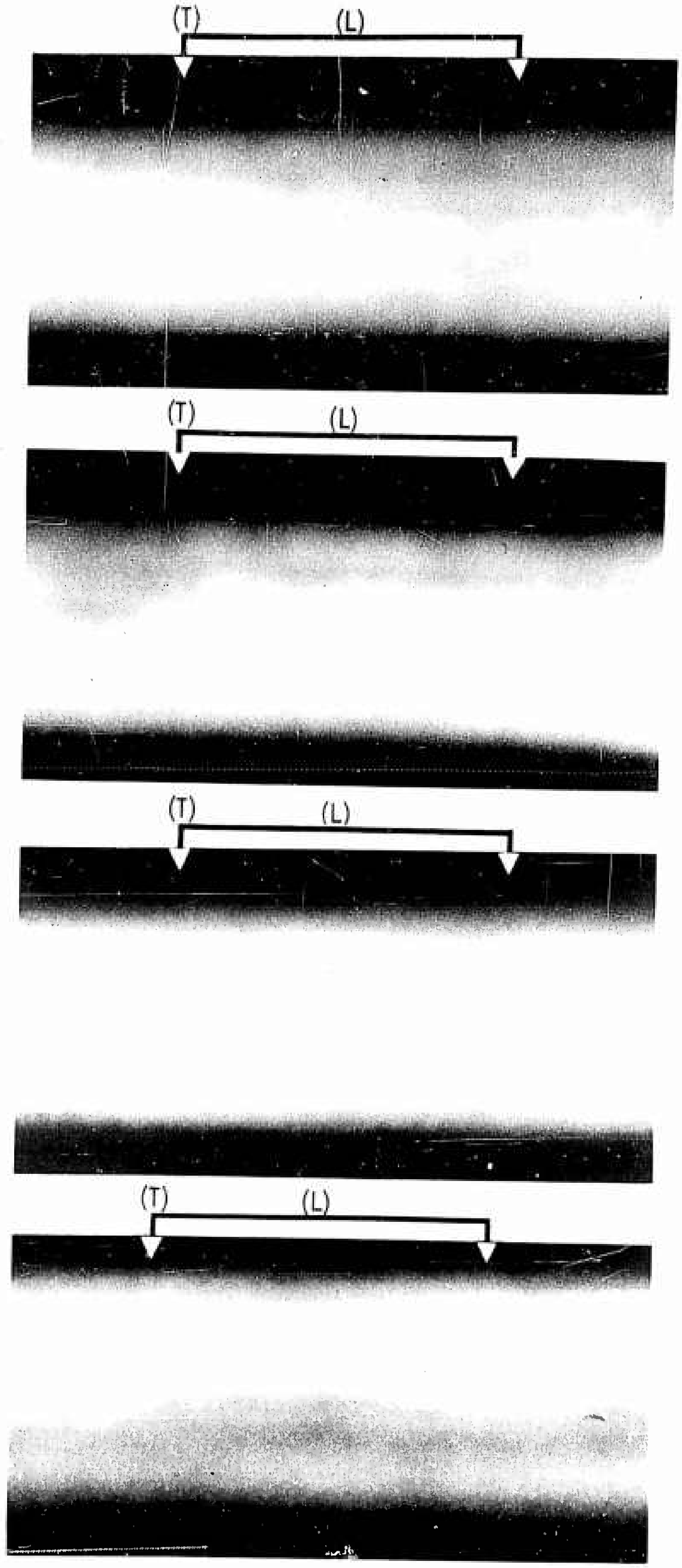
(b)
Radiograph of 1 4" Thick
Transverse Section



(c)
Macro-Section
Caustic-Fluoride Etch

Figure 7

RESULTS OF RADIOGRAPHIC AND MACRO-EXAMINATION OF A WELD IN 1-1 4 INCH 5083 ALLOY WHICH CONTAINED A VARYING AMOUNT OF LACK OF ROOT FUSION ALONG THE WELD LENGTH

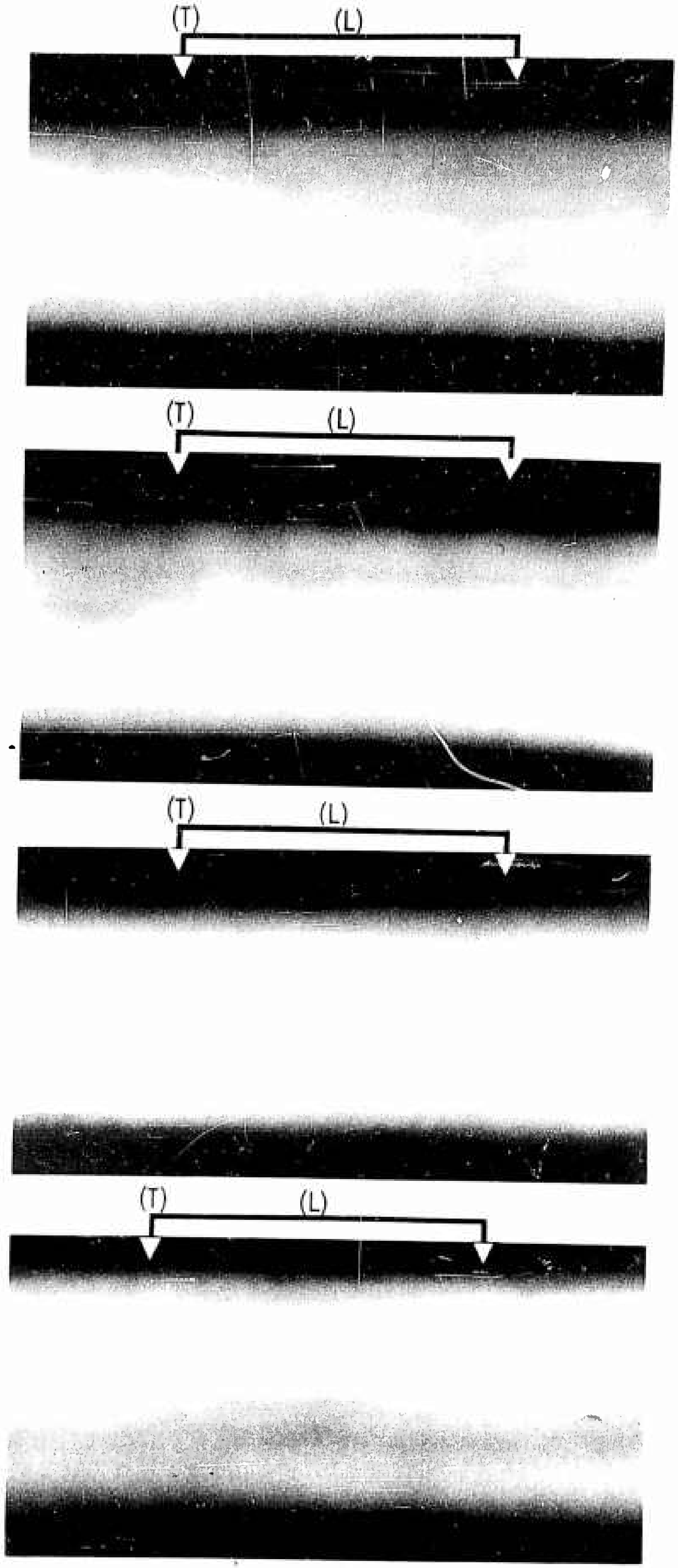


(a)

Conventional Radiograph

(T) = Location of transverse fracture

(L) = Length of weld included in longitudinal fracture

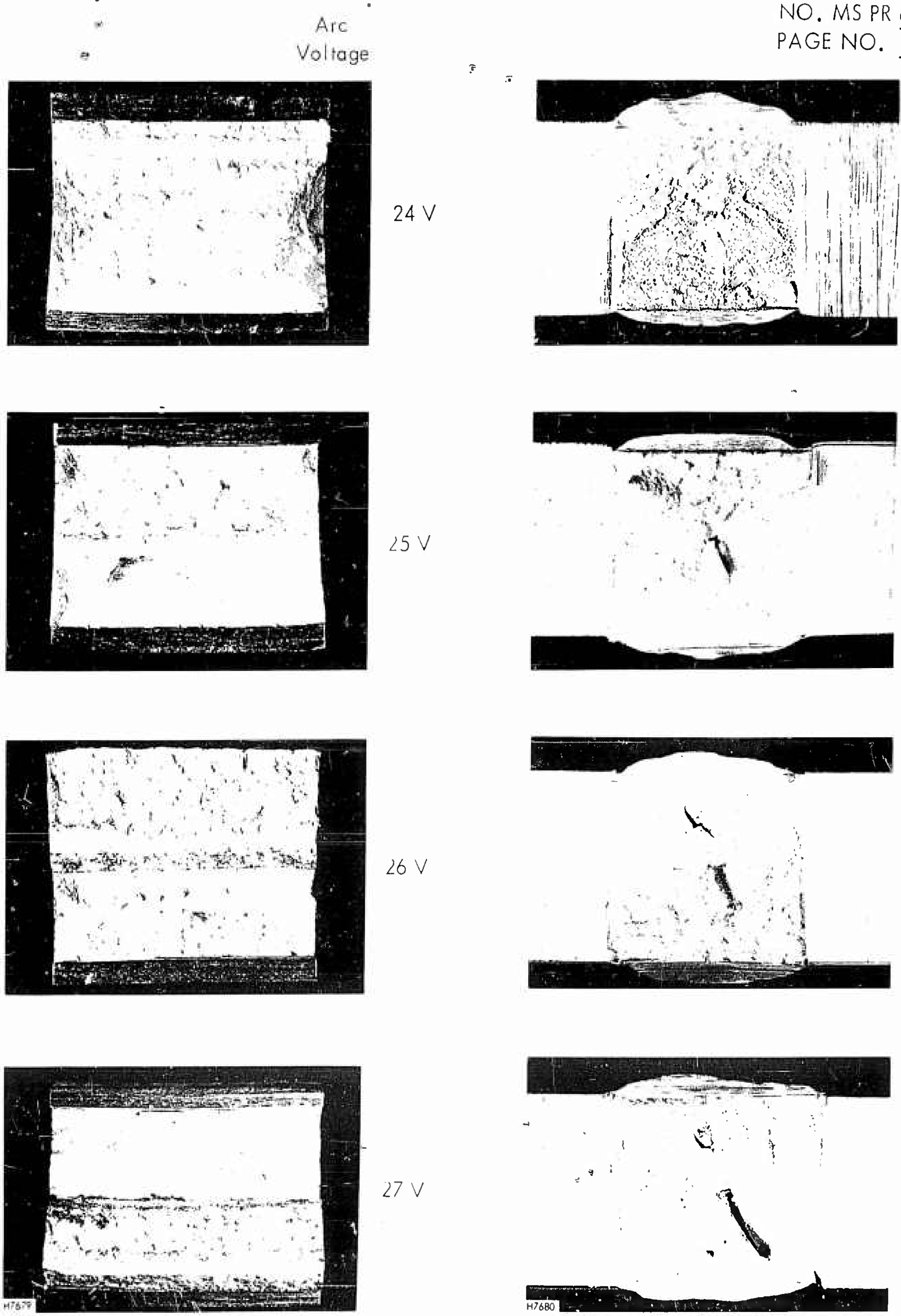


(a)

Conventional Radiograph

(T) = Location of transverse fracture

(L) = Length of weld included in longitudinal fracture



(b)
Longitudinal Fracture

(c)
Transverse Fracture

Figure 8

RESULTS OF RADIOGRAPHIC AND FRACTURE EXAMINATION OF WELDS CONTAINING VARIOUS QUANTITIES OF DROSS FILMS

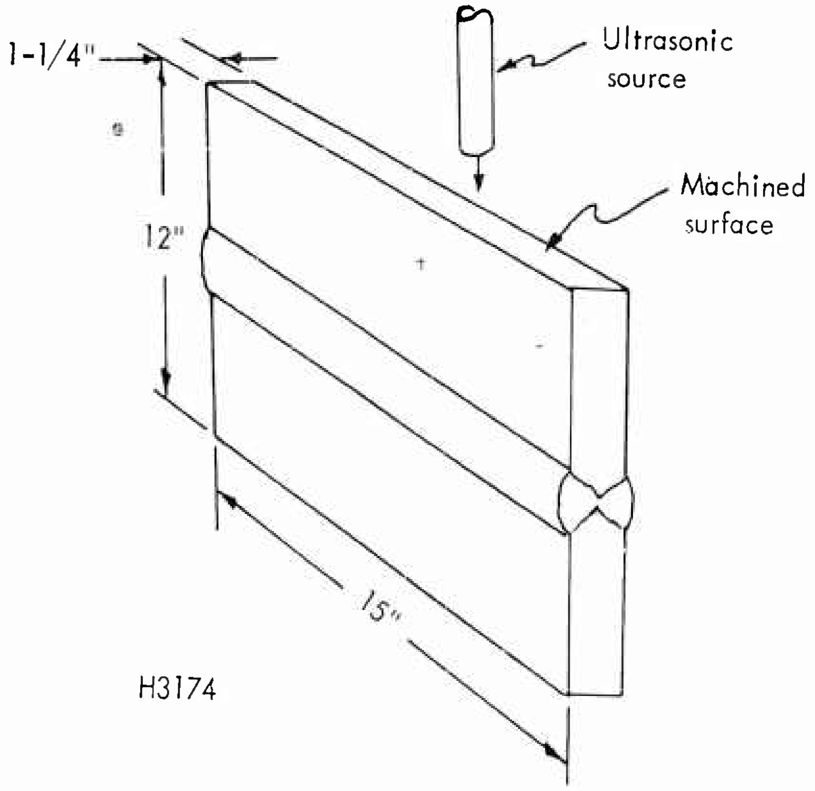


Figure 9
SKETCH ILLUSTRATING DIRECTION OF ULTRASONIC TEST

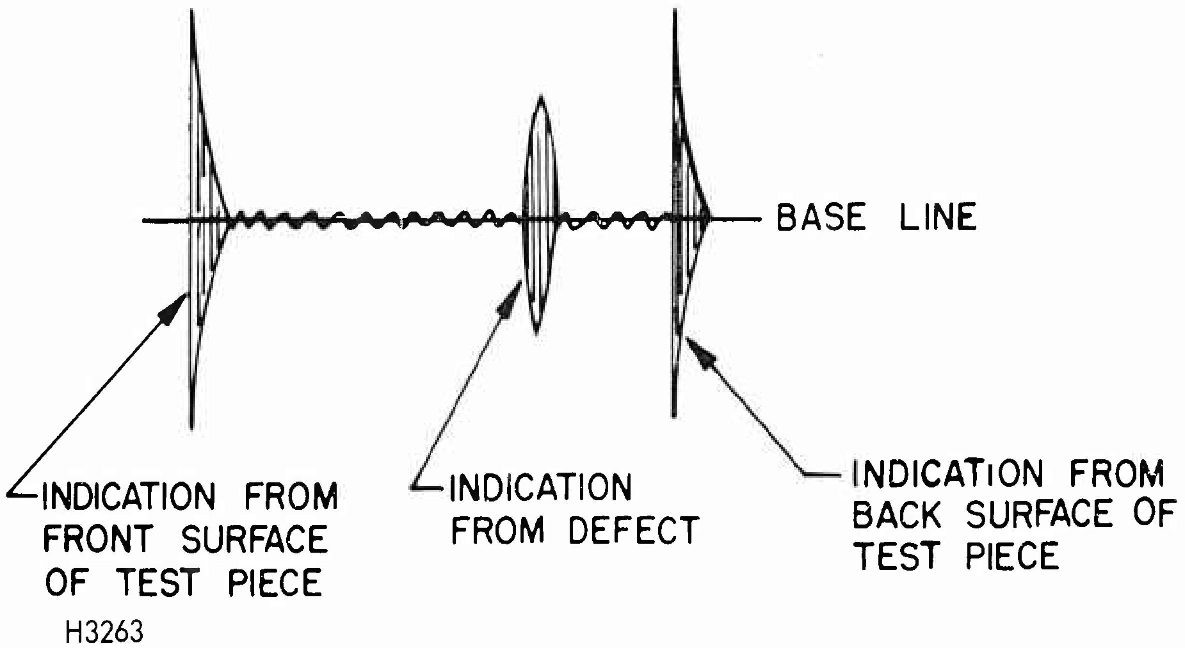
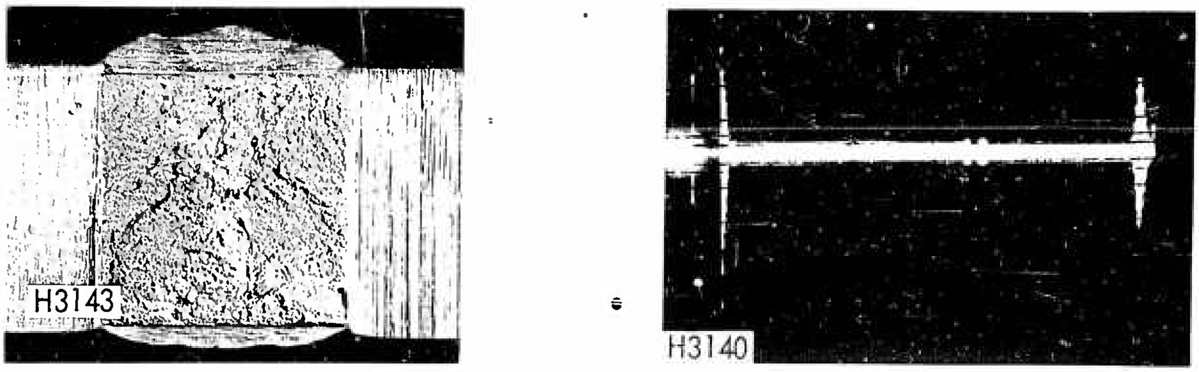
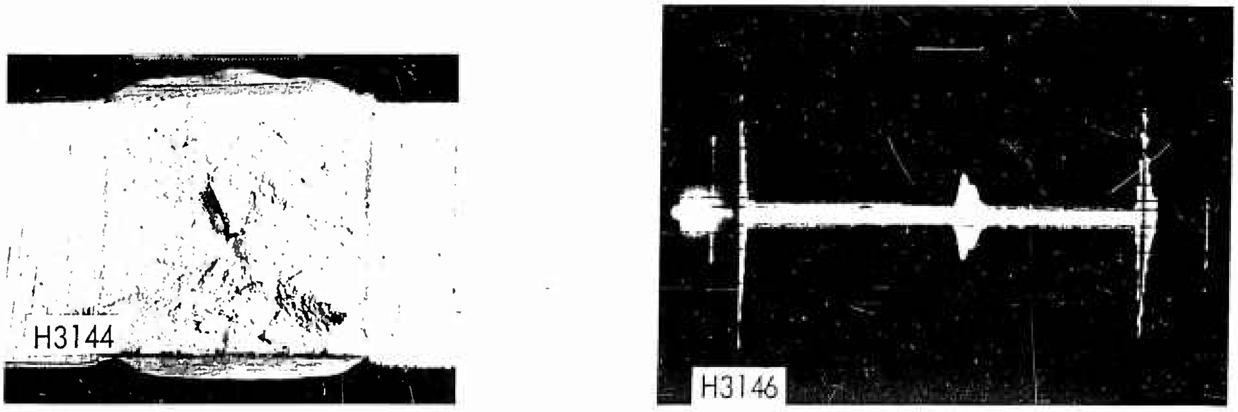


Figure 10
SKETCH OF REFLECTOSCOPE CATHODE RAY TUBE TRACE

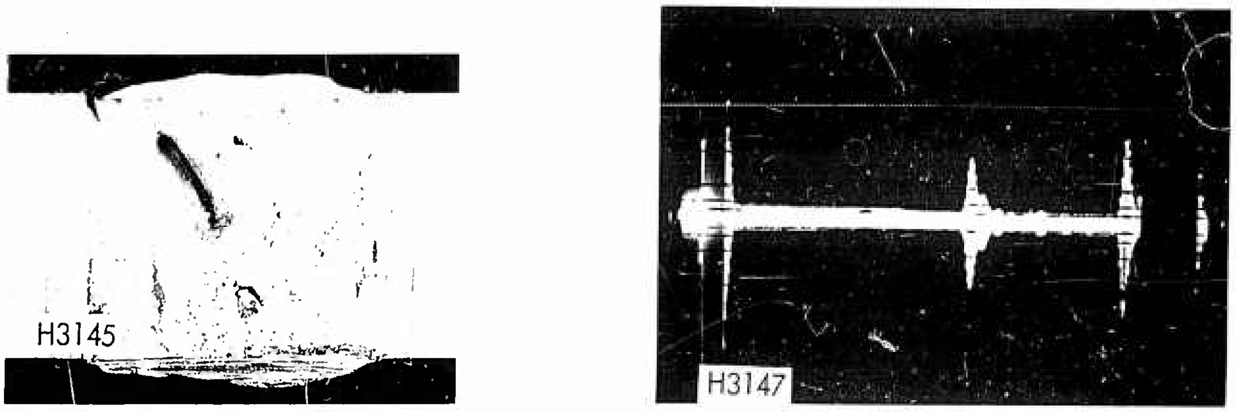
Transverse Weld Fractures | Typical Ultrasonic Response Patterns



(a) Control Weld (No Defects)



(b) Moderate Dross Films

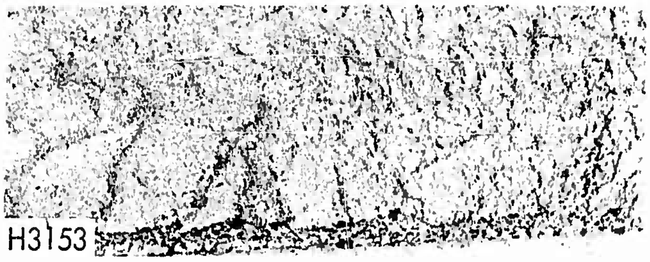


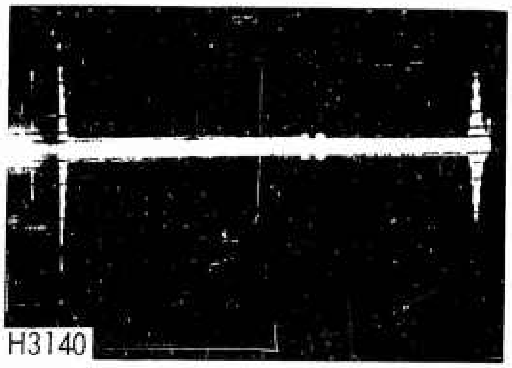
(c) Severe Dross Films

Figure 11
DROSS FILM SERIES
Extent of Weld Defects as Determined From Weld Fracture and Ultrasonic Examinations

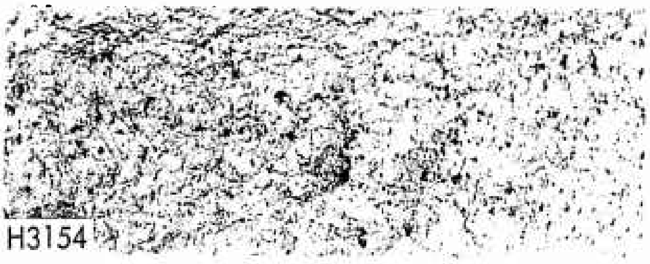
Typical Ultrasonic Response Patterns

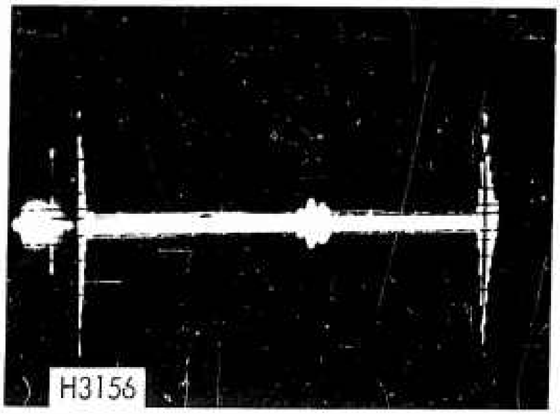
Longitudinal Weld Fractures



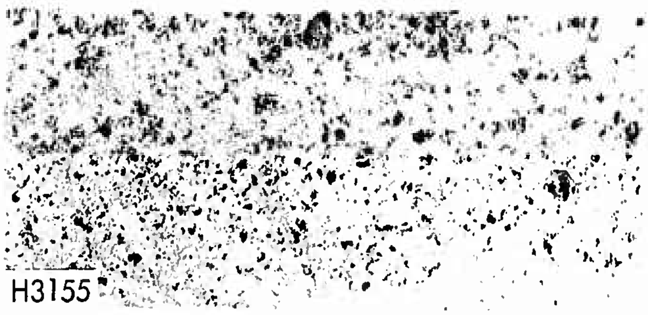


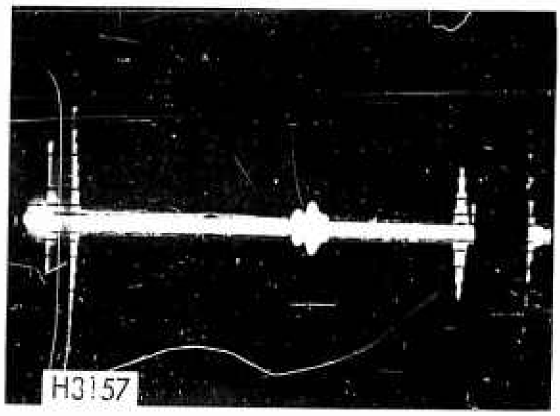
(a) Control Weld (No Defects)





(b) Moderate Fine Dross





5X

(c) Severe Fine Dross

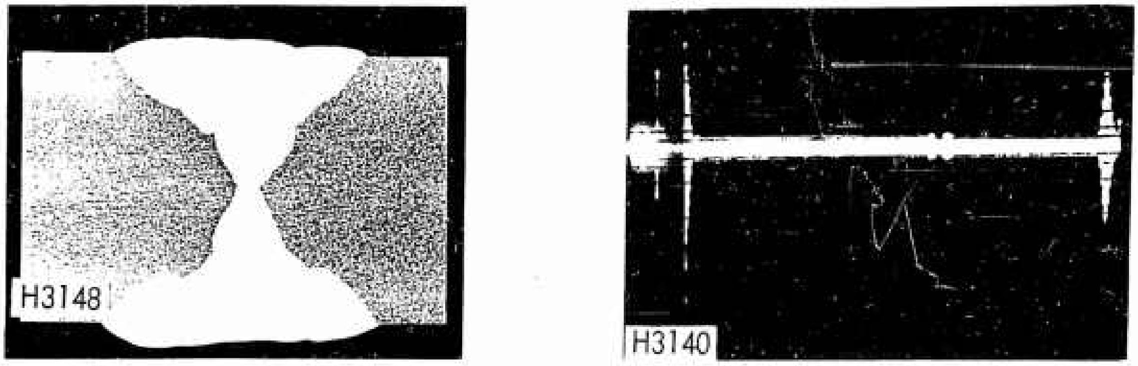
Figure 12

DISTRIBUTED FINE DROSS SERIES

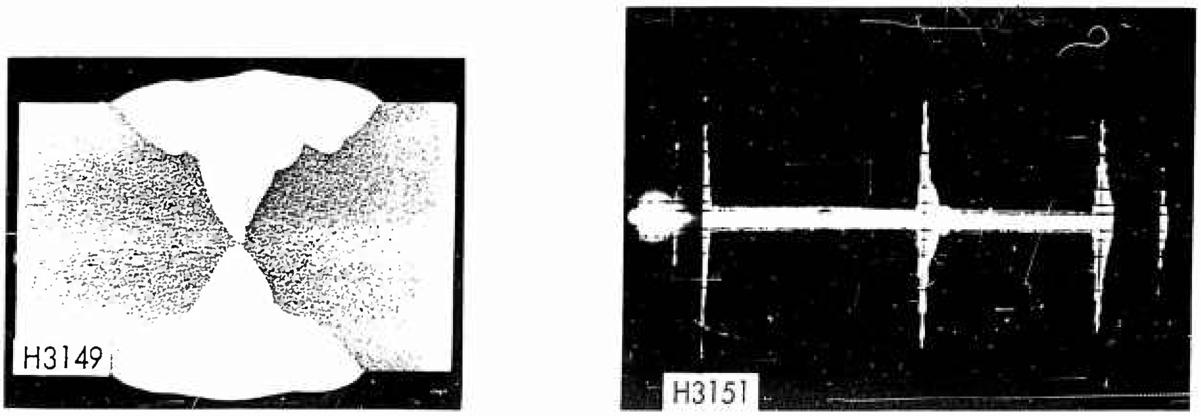
Extent of Weld Defects as Determined From Weld Fractures and Ultrasonic Examinations

Transverse Macrosections

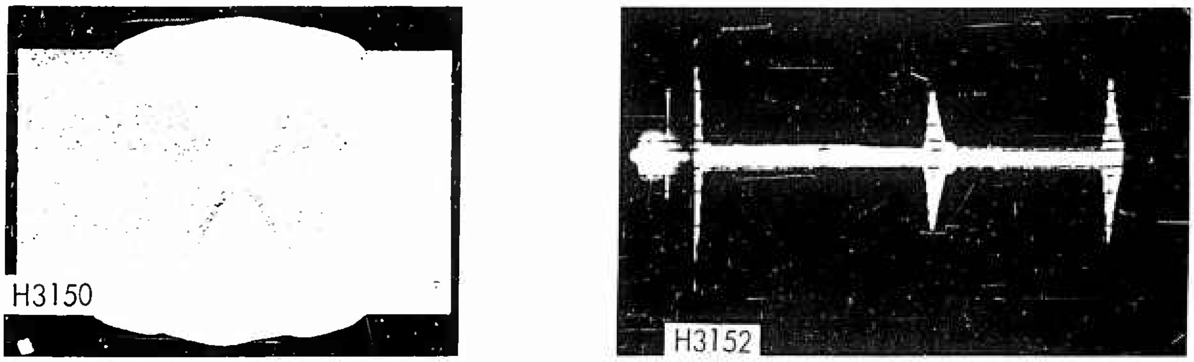
Typical Ultrasonic Response Patterns



(a) Control Weld (No Defects)



(b) Moderate Lack of Fusion



Caustic Fluoride Etch

(c) Severe Lack of Fusion

Figure 13
LACK OF ROOT FUSION SERIES
Extent of Weld Defect as Determined From Transverse Macrosection and Ultrasonic Examinations

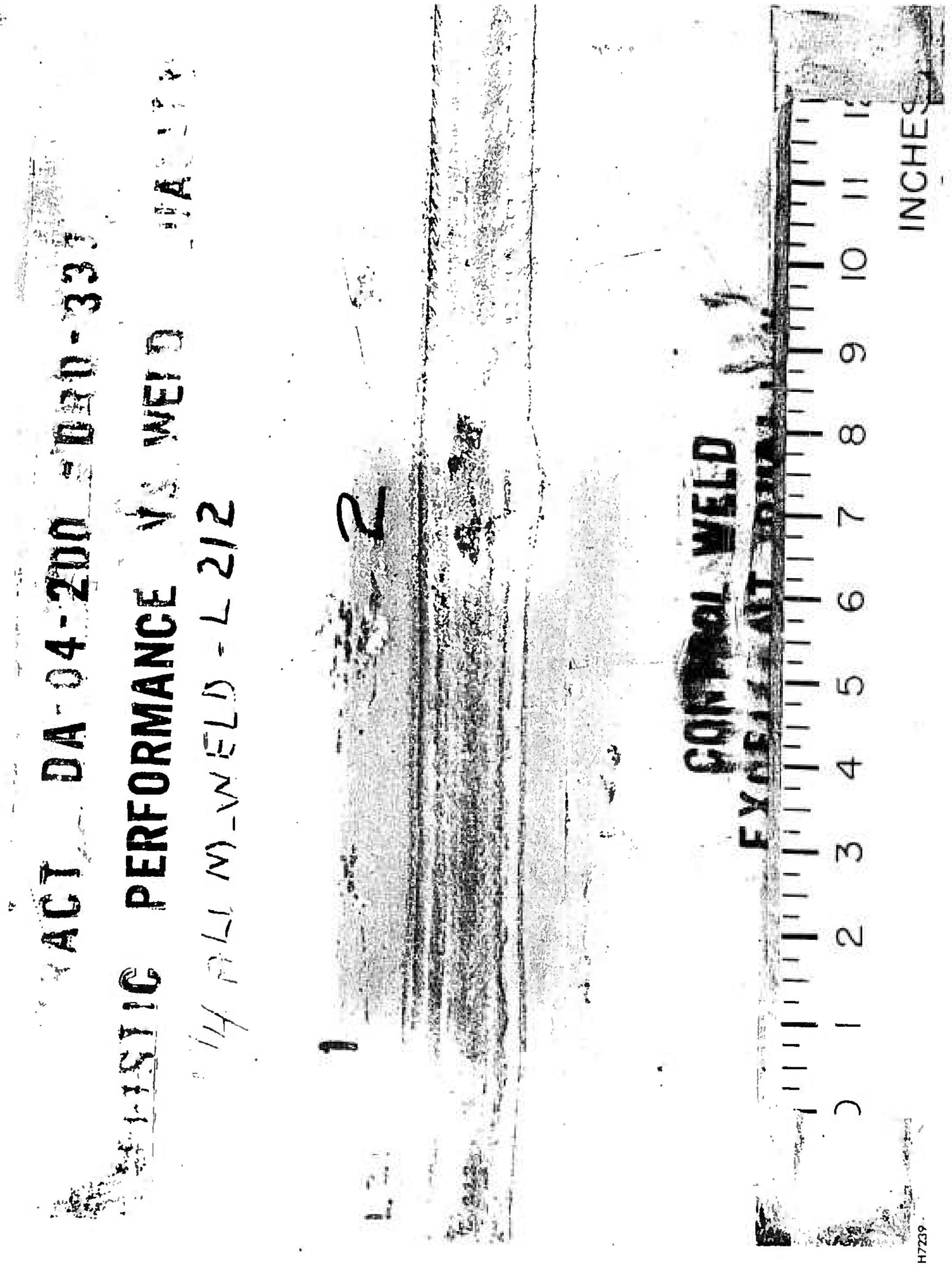


Figure 14
BACK SURFACE OF CONTROL WELDMENT L212 AFTER BALLISTIC SHOCK TEST
Thic weldment contained no weld defects

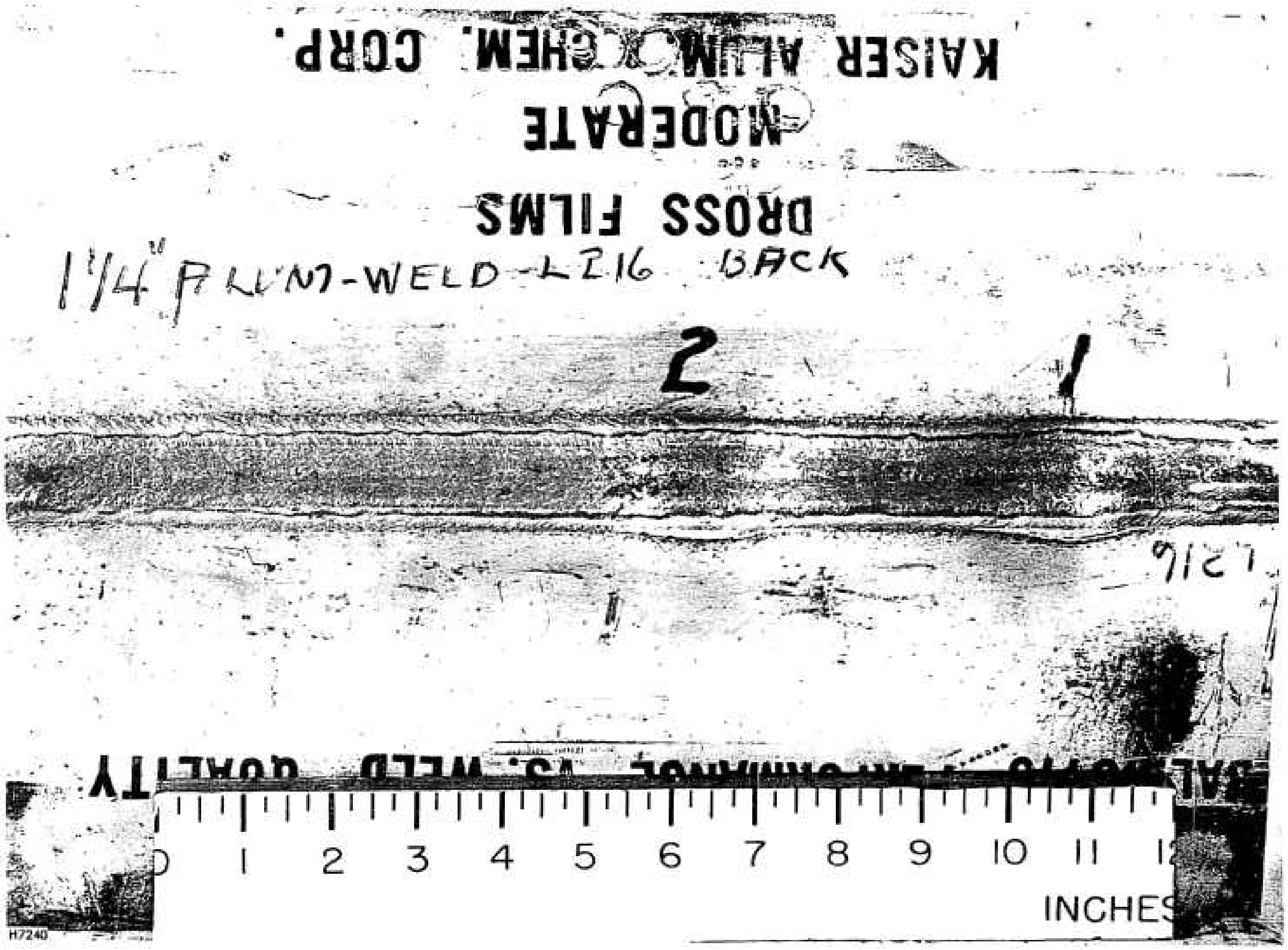


Figure 15
BACK SURFACE OF WELDMENT L216 AFTER BALLISTIC SHOCK TEST
This weldment contained moderate dross films

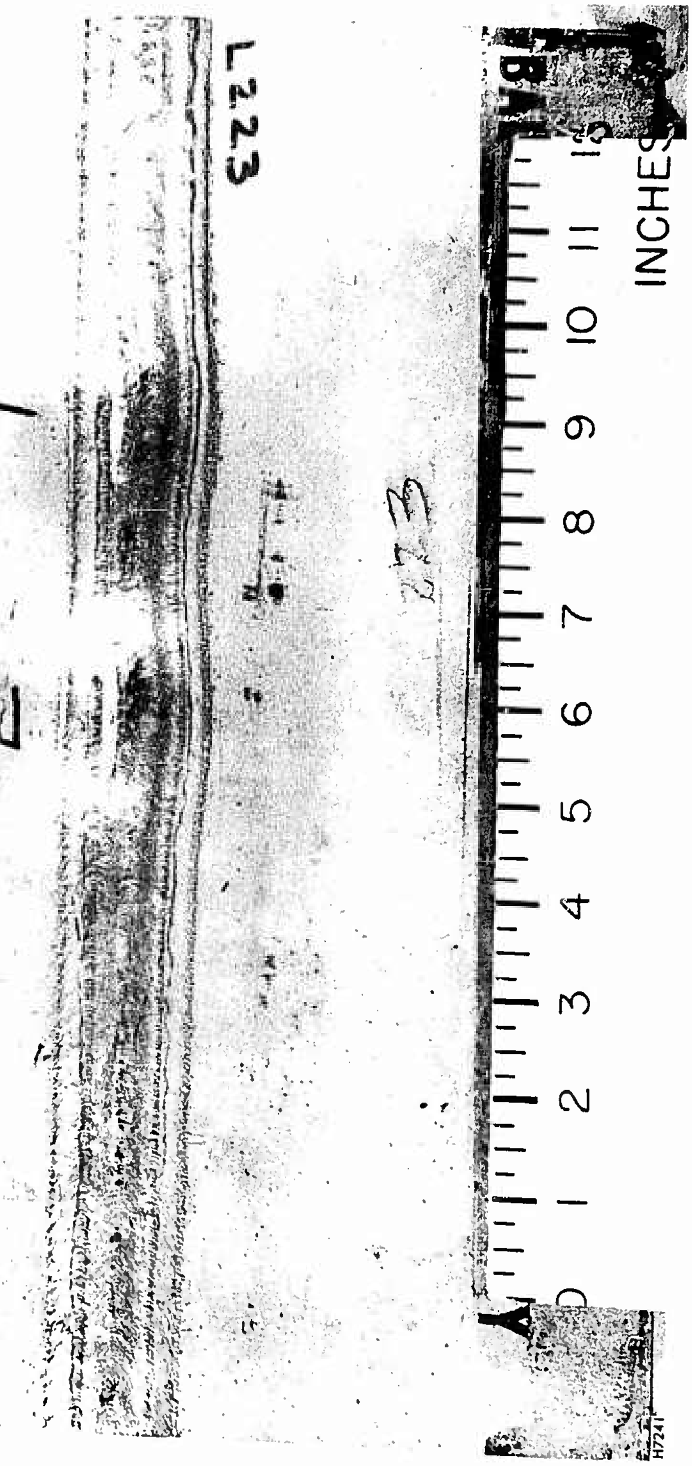


Figure 16
BACK SURFACE OF WELDMENT L223 AFTER BALLISTIC SHOCK TEST
This weldment contained moderate lack of fusion

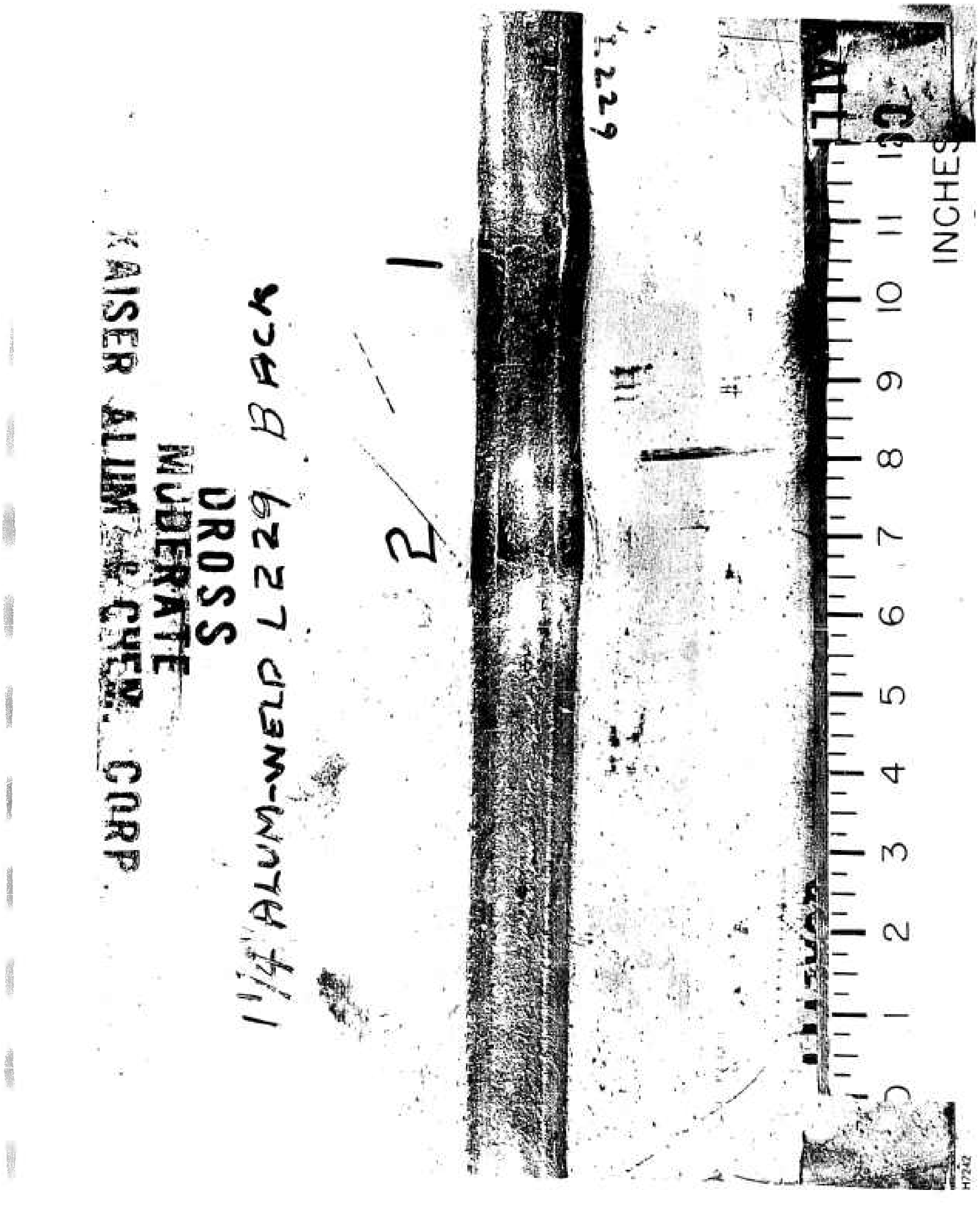


Figure 17
BACK SURFACE OF WELDMENT L229 AFTER BALLISTIC SHOCK TEST
This weldment contained moderate scattered dross

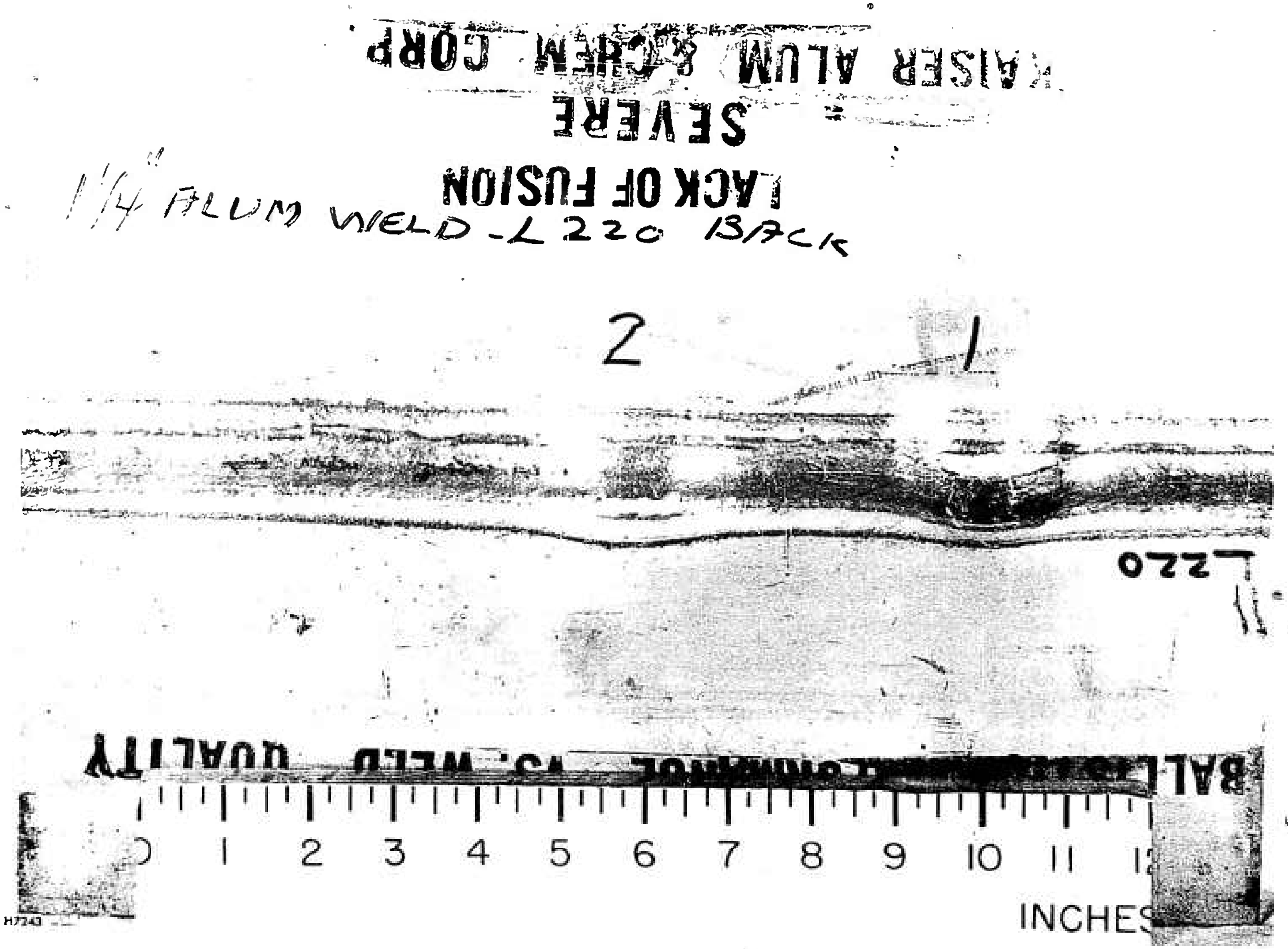


Figure 18

BACK SURFACE OF WELDMENT L220 AFTER BALLISTIC SHOCK TEST

This weldment contained severe lack of fusion

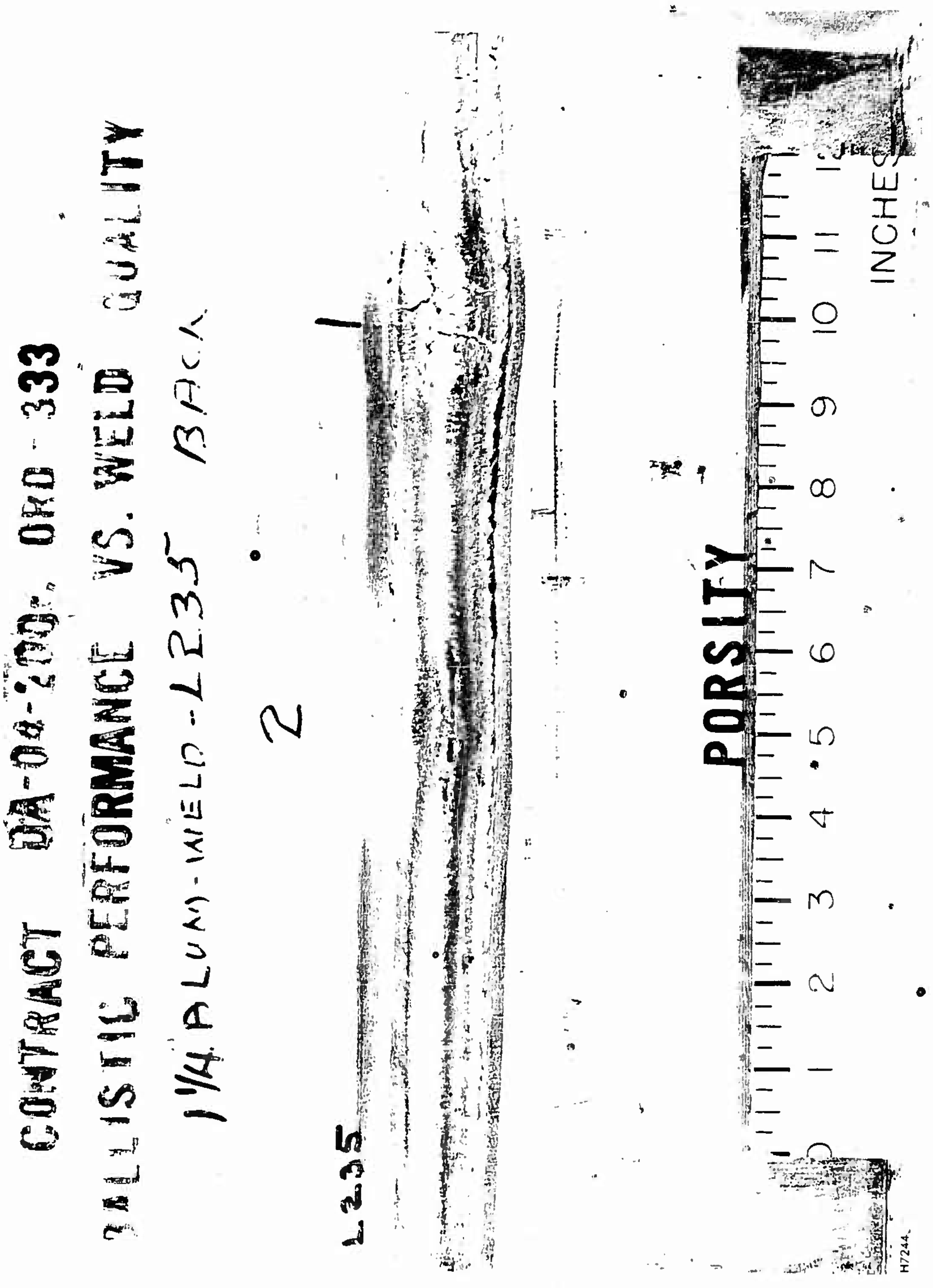


Figure 19
BACK SURFACE OF WELDMENT L235 AFTER BALLISTIC SHOCK TEST
This weldment contained severe porosity

Figure 20
BACK SURFACE OF WELDMENT L240 AFTER BALLISTIC SHOCK TEST
This weldment contained moderate porosity

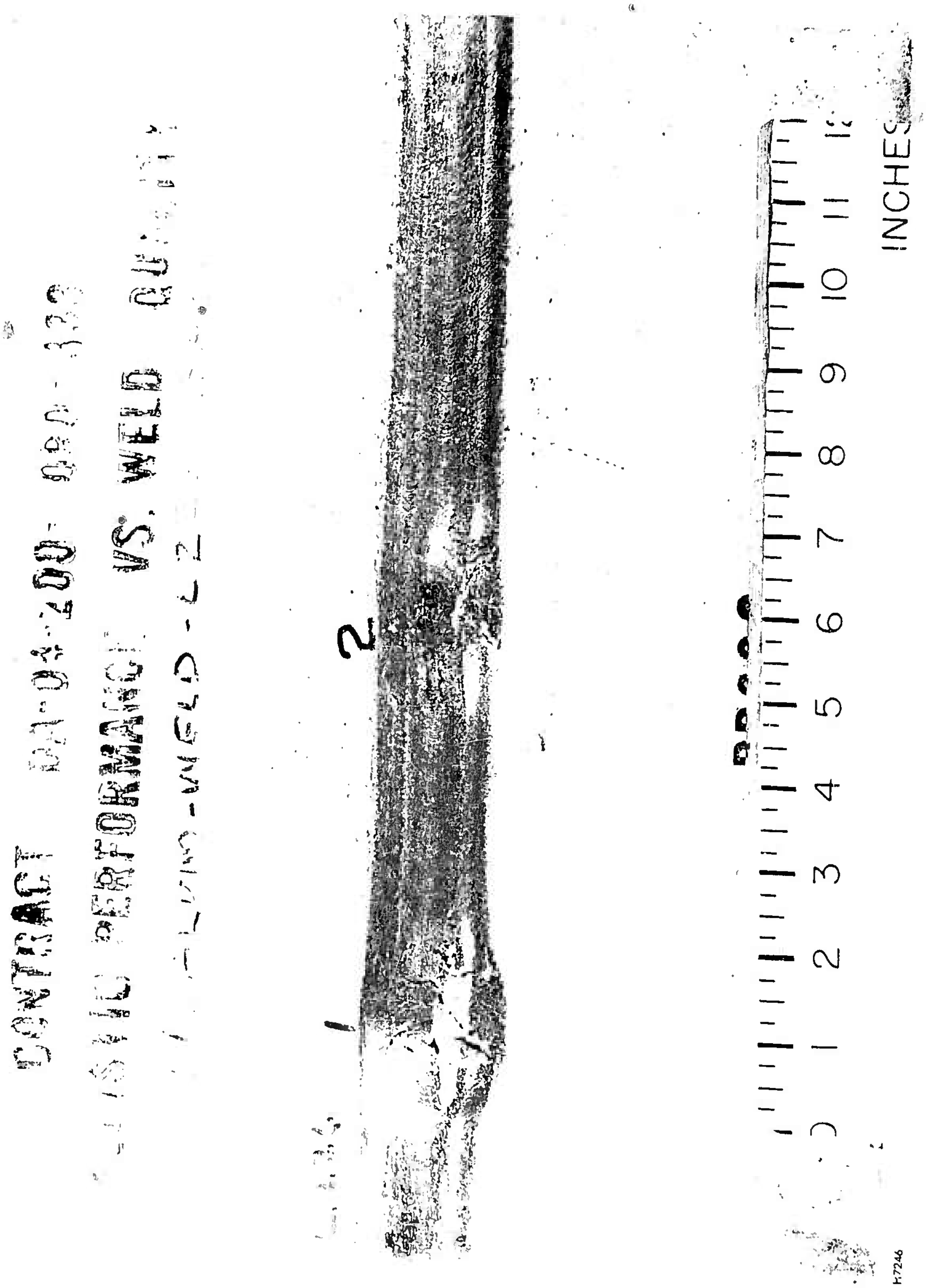


Figure 21
BACK SURFACE OF WELDMENT L226 AFTER BALLISTIC SHOCK TEST
This weldment contained severe scattered dross

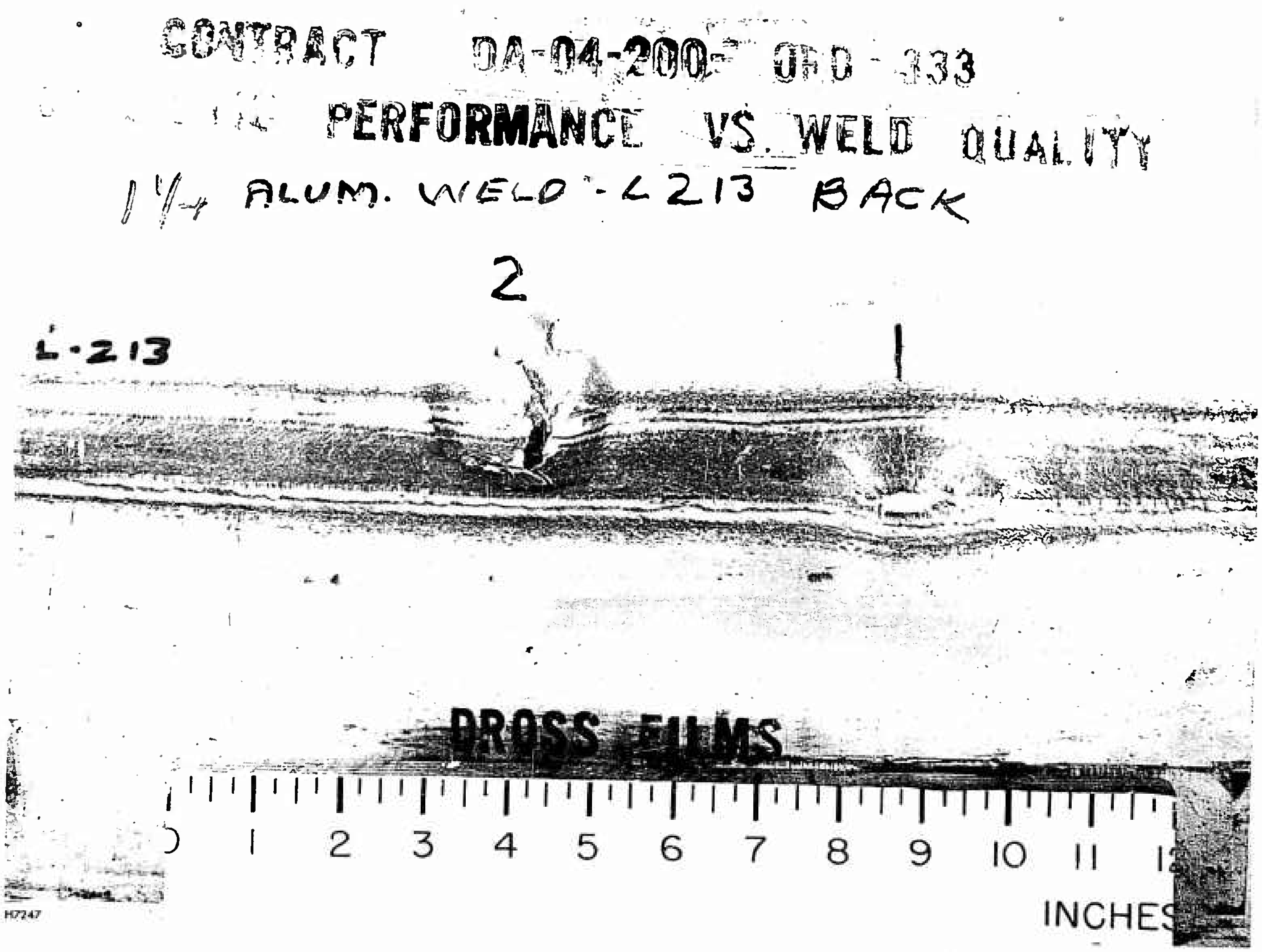


Figure 22

BACK SURFACE OF WELDMENT L213 AFTER BALLISTIC SHOCK TEST
This weldment contained severe dross films